PORAP: AN ENERGY AWARE PROTOCOL FOR CYCLIC MONITORING WSNS

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PoRAP: An Energy Aware Protocol for Cyclic Monitoring WSNs

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Abstract

This work starts from the proposition that it is beneficial to conserve communication energy in Wireless Sensor Networks (WSNs). For WSNs there is an added incentive for energy efficient communication. The power supply of a sensor is often finite and small. Replenishing the power may be impractical and is likely to be costly.

Wireless Sensor Networks are an important area of research. Data about the physical environment may be collected from hostile or friendly environments. Data is then transmitted to a destination without the need for communication cables. There are power and resource constraints upon WSNs, in addition WSN networks are often application specific. Different applications will often have different requirements. Further, WSNs are a shared medium system. The features of the MAC (Medium Access Control) protocol together with the application behaviour shape the communication states of the node. As each of these states have different power requirements the MAC protocol impacts upon the operation and power consumption efficiency.

This work focuses on the development of an energy conservation protocol for WSNs where direct communication between sources and a base station is feasible. Whilst the multi-hop approach has been regarded as the underlying communication paradigm in WSNs, there are some scenarios where direct communication is applicable and a significant amount of communication energy can be saved. The Power & Reliability Aware Protocol has been developed. Its main objectives are to provide efficient data communication by means of energy conservation without sacrificing required reliability. This has been achieved by using direct communication, adaptive power adaptation and intelligent scheduling.

The results of simulations illustrate the significance of communication energy and adaptive transmission. The relationship between Received Signal Strength Indicator (RSSI) and Packet Reception Rate (PRR) metrics is established and used to identify when power adaptation is required. The experimental results demonstrate an optimal region where lower power can be used without further reduction in the PRR. Communication delays depend upon the packet size whilst two-way propagation delay is very small. Accurate scheduling is achieved through monitoring the clock drift.

A set of experiments were carried out to study benefits of direct vs. multi-hop communication. Significant transmitting current can be cserved if the direct communication is used. PoRAP is compared to Sensor-MAC (S-MAC), Berkeley-MAC (B-MAC) and Carrier Sense Multiple Access (CSMA). Parameter settings used in the Great Duck Island (GDI) a production habitat monitoring WSNs were applied. PoRAP consumes the least amount of energy.

Candidate's declarations

I, Mr. Ittipong Khemapech, hereby certify that this thesis, which is approximately 86,000 words in length, has been written by me, that it is the record of work carried out by me and that it has not been submitted in any previous application for a higher degree.

I was admitted as a research student in September 2004 and as a candidate for the degree of PhD in Computer Science in September 2004; the higher study for which this is a record was carried out in the University of St Andrews between 2004 and 2011.

Date 15 April 2011   Signature of candidate

Supervisor's declarations

I hereby certify that the candidate has fulfilled the conditions of the Resolution and Regulations appropriate for the degree of PhD in Computer Science in the University of St Andrews and that the candidate is qualified to submit this thesis in application for that degree.

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Chapter 1

Introduction

Energy conservation is currently growing in importance. This dissertation focuses on the issue of energy conservation within the domain of Wireless Sensor Networks (WSNs). There are also specific reasons why energy conservation is more important for WSNs than for other types of networks. A WSN consists of multiple sensors which are able to sense some aspect of their environment and communicate their readings to a base station or sink without being physically connected to it. Sensors are often also resource constrained, being small in size and relying on small batteries for power. Consequently, the efficient utilisation of energy should be an important priority for designing WSN network protocols. This differs from the traditional approach to designing network protocols where issues like survivability, maximising throughput or reliability have been prioritised. Making energy conservation an important design priority is a new approach.

This chapter is organised into a number of sections. Collectively these describe the problem space that the work addresses, give an overview of the work that has been conducted and provide a detailed guide to the contents of each chapter.

- **Thesis overview**: provides a picture of this work. Current WSN deployments, together with challenges in protocol design and the key elements of PoRAP are described.

- **Problem definition**: provides a statement of the problem that this dissertation addresses. PoRAP aims for minimising communication energy without compromising the packet reception rate. The application class that this work focuses on is periodic-based sensors such as an environmental monitoring system where readings are taken and transmitted cyclically.

- **Thesis statement**: A statement of the thesis is given in this section.

- **Hypotheses**: Several hypotheses are made in this work. They will be used during protocol design and evaluated by experiments which are described in later chapters.

- **Main contributions**: these fall into four groups; a survey of power aware protocols for WSNs, investigation of the relationships between metrics for monitoring communication, design of the protocol and experimental work.

- **Methodology**: here the work that has been conducted in support of the thesis is outlined. This includes specification of the tools that have been used and an overview of the software that has been developed.

- **Organisation of the thesis**: There is a detailed summation of each of the nine chapters. Leaving aside the introduction, future work and concluding chapters, they are: an introduction to WSNs, a survey of related work, discussion of design issues, the design and implementation, an evaluation chapter and a comparison with other energy aware WSN protocols.

1.1 Thesis Overview

This work starts from the proposal that energy efficient communication in WSN is beneficial. For WSNs there is an added incentive for energy efficient communication. The power supply of a sensor is often finite and small. Replenishing the power may be impractical and is likely to be costly.

Wireless sensor networks (WSNs) are an important research area with a major technological impact [Tec03]. Several surveys have addressed sensor components, technological background, protocol developments and research challenges [ASSC02(a)(b), CES04, CK03, KDM05]. With significant breakthroughs in “Micro Electromechanical Systems”, or MEMS, [WP02], sensors are becoming smaller. It is feasible to fit them into a smaller volume with more power and less production costs. WSNs may be deployed in a wide range of different environments. These include remote and hostile environments as well as local and friendly ones.

A major driving force behind research in WSNs has been military and surveillance applications. Recently, however diversification has occurred with the development of civilian applications. One example which is used as a reference point throughout this dissertation is Great Duck Island (GDI). Sensors were scattered over a remote island in [MPS+02] to monitor the seabird’s migration. In another example WSNs were deployed around volcanoes [ALR+06]. Such applications illustrate the usefulness of WSNs which make data collection feasible from remote and hostile environments with minimal human intervention. Moreover, WSNs can be used in local and non-hostile areas; for example to build a smart classroom or home [Ess00, SMP01] or the measurement of patients biometrics through attached sensors [JLR+03, OMSJ06].

There are four key issues which should be investigated when designing and developing a protocol for WSNs.

1. Resource constraint is one of the main challenges of WSNs as the required power or energy for all operational aspects is often provided by small batteries. Under some circumstances, especially in unfriendly environments, sensors are normally expected to operate by themselves after deployment with minimum human intervention or maintenance. Battery recharge or replacement is either infeasible or costly. Power conservation is therefore an essential concern to WSNs research and development.

2. The specific application requirements, such as reliability and data rate, should be considered. Applications may be divided into two broad categories; those that respond to events and those that have a regular reporting cycle. Sensors deployed in a surveillance system may occasionally need to transmit bursts of data at a high rate. By contrast an environmental monitoring system may require regular low bandwidth communication of temperature and humidity readings.

3. Many sensors employ Radio Frequency (RF) for communication. Signal strength decreases with distance. It is difficult to use a model to accurately predict signal strength, even when transmission power and distance are known. This is because factors such as interference and reflection affect attenuation and the physical properties of the deployed area may not be known or may change. Thus the correct transmission power cannot always be accurately derived from a model. This poses the issue of using link quality monitoring and adaptive transmission power to determine signal strength and the required transmission power level.

4. Nodes in WSNs communicate via a shared medium. Medium access and utilisation is therefore crucial in protocol development. There are currently two major approaches including contention and schedule based. The medium is sensed prior to transmission in the contention based. A time slot is allocated for each source in the schedule based. One of the main objectives of both schemes is to avoid data collisions. The schedule based suits the cyclic monitoring WSNs as the sources are not required to collect the data often. The source can be in a sleep mode and wait for the others to complete their transmissions. The key issue is the determination of slot length.

One of the main objectives of WSNs power conservation is to minimise energy usage whilst other functional requirements such as reliability or time synchronisation are still achieved. Some authors argue that multi hop communication allows for deployment in scenarios where direct communication with a base station is not practical [ADB+04, ALR+06, CFP+06]. However, the spread of the Internet means that wireless devices may often communicate directly with a device that is connected to the Internet and has a reliable power supply. This work focuses on the design of wireless sensor networks protocols where direct communication with a powered base station is feasible and data is sent from the sensors to the base station at regular intervals. There are several important scenarios where such two assumptions hold.

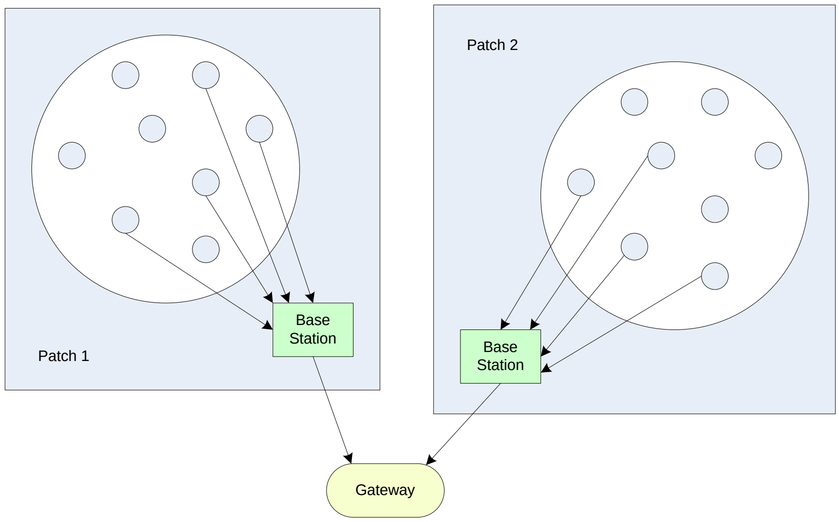


Figure 1.1: Possible direct communication scenario in Great Duck Island [MPS+02]

For example, in the Great Duck Island (GDI) [MPS+02] experiment, direct communication can be used in each patch as shown in Figure 1.1. In GDI the sensors transmit at five minute intervals. The sensors can switch their transceivers on for data communication and turn to sleep mode to conserve energy. After collecting data from its sources, the base station sends the data to a gateway for further operations. A further example is scattering sensors in a building and measuring temperature at specific intervals. Direct communication can be applied to each room or the whole floor depending upon the presence and location of barriers.

This research work specifically looks at WSNs where direct communication is possible and beneficial. A protocol for WSNs, PoRAP, is developed and provides energy efficient data delivery, without increasing packet loss. In designing PoRAP several experiments were conducted to establish the relationship between transmission power, reception signal strength and packet reception success. These showed a strong correlation between Received Signal Strength Indicator (RSSI) and Packet Reception Rate (PRR). In PoRAP, the RSSI is monitored at the base station. If the RSSI is too high the base station signals the sensor to reduce its transmission level, thereby saving power. If the RSSI is too low the base station signals the sensor to increase its transmission level so that packet loss is avoided.

PoRAP adopts a schedule based scheme for the sources' transmissions. It is assumed that nodes will be reporting measurement data regularly back to the base station. Each reporting interval consists of three time periods. In the first the base station sends a configuration packet. This informs nodes whether they are to increase, decrease or leave unaltered their transmission levels.

There are then slots, each of which contains a data slot within which a sensor may transmit its data to the base station. There may then be a period of quiet before the start of a new cycle. Delays and clock drifts are measured so that nodes know when to wake up to listen and transmit. Delays depend upon payload size whilst the drifts are hardware dependent and non-deterministic.

The amount of energy that can be saved by PoRAP when compared to a multi hop network increases with the density of sensor deployment. The design aims to optimise energy conservation rather than system throughput, in many sensing scenarios high throughput is not required. Sensors collect and report some physical data such as temperature and humidity. In such cases, the data reporting rate may be in minutes or hours. Two packet structures are used in PoRAP. The control packet is used in control and setup phase. It contains essential information for transmission power adaptation and scheduling. The data packet is used to deliver the collected physical data back to the base station.

There are three main objectives in PoRAP evaluation. Firstly, potential benefits of direct communication are investigated by comparing it to multi-hop. The sources located more closely to the base station benefit the most in a direct communication scenario as they are transmitted at a lower power. Such nodes require more sending and receiving power for multi-hop communication. The sources at the farthest locations are not responsible for forwarding the packets from their neighbours, so they benefit the most from the multi-hop paradigm. Secondly, a network consisting of 20 sources and a base station was used to test PoRAP performances. Lower transmission power can be used to achieve the RSSI settings without reducing the PRR. According to the results, the RSSI over -70 dBm often provides a PRR of nearly 100%. The dBm is the measurement of power loss in decibels (dB) using 1 milli-watt (mW) as a reference value. Finally, clock drifts were analysed. They increase with duration between two consecutive transmissions. By knowing the medians, the sources can adjust their schedules in order to synchronise with the base station. The duty cycle can therefore be reduced.

In summary, direct communication can be considered a communication paradigm for wireless sensor networks, which offers improved energy conservation. Dense topologies benefit from fewer transmissions and receptions than the multi-hop. PoRAP has been specifically developed for direct communication scenarios and provides efficient data delivery mechanisms in terms of energy conservation.

1.2 Problem Definition

A statement of what the problem is that this dissertation addresses is as follows:

In order to develop an energy aware protocol for WSNs without compromising required reliability, several observations and limitations should be made and addressed. Transmission *power can be adapted using a Transmission Power Control (TPC) scheme. However, transmitting at a lower power may not achieve the required reliability. The relationships between them and other important factors such as distance and reception strength must be established. In direct communication, the base station controls the operation of its sources. Control signals are included in its packet. The signaling size is limited by the buffering capacity of the transceiver. Transmissions of the sources can be scheduled by the base station. The schedule-based approach can be used. A time slot is allocated for a source. However, slot's size must be large enough to cover relevant communication delays. Otherwise, collisions will occur. Time synchronisation is very important in the schedule-based. Clock drift occurs as the local clock of the sensor is running at a different speed. It can be accumulated into a significant amount and time synchronisation is no longer maintained.*

Several key issues affecting protocol development for WSNs are outlined in this section. PoRAP aims for energy conservation by making the sources send at the minimum power that does not increase packet loss. Packets transmitted at higher power levels tend to be successfully received at their destination. The maximum transmission power can be used throughout a sensor's lifetime but the embedded batteries would run out of power more quickly. However, lower power can be used but packets may not be successfully delivered to their destination. The first challenge of PoRAP design is how to balance energy conservation and reliability awareness. The adapted transmission power should not reduce successful data reception. Reliability is considered to be a link quality metric and it is defined as the ratio of the number of received to that of sent packets. The base station may calculate reliability by monitoring both numbers. The number of sent packets is required from the sources and the base station can calculate only after packet reception. Alternatively, the base station may accurately predict reliability from the received signal strength.

The Tmote platform has been selected for this research and it employs CC2420 radio chip. Two metrics including RSSI (Received Signal Strength Indicator) and LQI (Link Quality Indication) can be measured at data reception. The RSSI measurement is also offered by the CC1000 chip. Therefore, RSSI is mainly used in this research to demonstrate the received signal strength. Another metric, PRR (Packet Reception Rate), is more closely related to reliability. Several experimental studies are required to establish the relationship between link quality metrics but reliability may be defined from such relationships in terms of received signal strength. The required strength is recognised by the base station and it will be used for the power adaptation.

The power adaptation notification mechanisms are also important and are limited by the allowable packet size. The buffer capacity of CC2420 is 128 bytes. The chosen operating system is TinyOS 2.0.2. The header and footer sizes are approximately 11 bytes; this leaves a maximum payload size of 117 bytes. PoRAP is intended to support a significant number of sources. Instead of employing the whole byte for a source, only some bits are used for the notification. The current transmission power may be unchanged, increased or decreased. Therefore, two bits are sufficient and a significant number of sources may be supported by a base station.

In a wireless direct-communication network the problem of how to efficiently share the medium arises, policies need to be established to avoid sources of power wastage such as collisions and idle listening. The schedule based approach is suitable where a slot is allocated for each source. At a specific time, only one source engages the medium for data transmission and therefore collision can be avoided. Idle listening power is minimised as the source only starts the radio to receive the broadcasted control packet and it sends a data packet when its slot arrives. Several timer components in TinyOS are required for scheduling the radio start and stop. Time synchronisation is also important as nodes have to agree upon the synchronised schedule. Each sensor has an oscillator which generates clock signal in ticks. The clocks of different sensors may run at different speeds and clock drift may occur. The drift becomes important as it may accumulate into seconds if the sources operate for a long time.

1.3 Thesis Statement

The thesis statement of this dissertation is that:

"Significant gains in power conservation can be achieved by designing WSN protocols to meet particular application classes. Specifically, that combining direct communication, power adaptation and intelligent scheduling is appropriate for sensor networks spread over moderate distances with regular reporting patterns where energy conservation is a prime requirement."

1.4 Hypotheses

This dissertation focuses on design and development of an energy aware protocol for WSNs. Prior to the design, several hypotheses are made and they are outlined in this section. PoRAP aims for an efficient data delivery in terms of energy conservation without further reduction in the reliability measurements. The main goal is to keep the network operating at an optimal region most of the time. Energy conservation and no further data loss are achieved in a region which can be found in the relationships between link quality metrics. Transmission power adaptation is already supported by the recent transceivers including CC2420, the chosen radio in Tmote platform which is used in this dissertation [CC2420].

Apart from the power adaptation, PoRAP adopts the schedule-based scheme. Time synchronisation between sources and base station is required. This can be conducted by referring to the timestamps at the MAC layer. The size of time slot must be large enough to cover transmitting and receiving delays. The delays should depend upon packet size. The source starts its radio for control reception and data transmission. It can be thus be in sleep mode else at other times. A frame is used to represent the communication cycle. Several timers provided by TinyOS can be used for the implementation.

PoRAP is developed with respect to several hypotheses as follows:

1. There are scenarios where WSNs can be run efficiently and effectively using direct communication between a base station and its associated sensors.

2. Fluctuation in link quality measurements provided by the radio chip, including RSSI (Received Signal Strength Indicator) and LQI (Link Quality Indication), should be monitored as not only distance but location is an important factor. These can be used to estimate the PRR (Packet Reception Rate). Several relationships between such metrics exist and power adaptation can be derived from this knowledge.

3. Synchronisation between sources and base station can be achieved by referring the scheduling to the timestamps at the MAC layer. The propagation delay which is computed from the MAC layer timestamps is very small.

4. In slot length determination the effect of distances should be minor as the propagation delay is assumed to be very small.

5. The costs of implementing transmission power adaptation and slot structure are less than the benefits of energy conservation.

In summary, several hypotheses are given. They shape the design and development of PoRAP. The relationships between metrics are useful to the design of transmission power adaptation. Measurements studies were required to confirm relationships reported in the associated literature [LZZ+06, SKPP07]. Timers and hardware controlling components can be used to implement the schedule-based protocol in PoRAP. Additional measurements were conducted to study the relationships between delays and packet size. The correctness of power adaptation and time synchronisation is tested. Such details are described later in this dissertation.

1.5 Main Contributions

This section outlines the main contributions of the work reported in this dissertation, which fall into four areas; a survey of energy aware protocols for WSNs, an investigation of the character of the relationship between link quality metrics, the design and development of a power and reliability aware protocol for direct communication WSNs with a cyclical reporting pattern, and fourthly, quantitative and comparative evaluation studies of the protocol.

1. A survey of power aware protocols for WSNs is carried out. Sensors are power and resource constrained as the power required for all operations is sourced from small batteries. There are two main areas of relevance.
    a. Medium Access Control (MAC) protocol is responsible for resolving contention as WSNs are shared medium systems. A MAC protocol should minimise major sources of energy wastage like collisions and idle listening.
    b. Transmission Power Control (TPC) benefits from the support for programmable transmission power the recent transceivers. A transmission power setting lower than the maximum can sometimes be used to save energy.

    The survey brings together those aspects of WSN work on MAC and TPC, which are relevant to the issue of power conservation.

2. The relationships between link quality metrics are established and then used in the design of a TPC protocol. The relationships between RSSI and PRR (Packet Reception Rate) remain stable across multiple environments. Thus the reliability that the application will experience in PRR can be inferred from RSSI taken over a small timespan. Thus if the RSSI reading is fed back to a sender this can be used to set the transmission power so that an appropriate PRR is achieved. Further the shape of the PRR and transmission power curve shows that after a threshold is reached little benefit can be obtained from increasing transmission power. The original contribution here lies primarily in demonstrating that the **relationship** between RSSI and PRR could be used in the design of an adaptive TPC which minimises power usage without compromising reliability.

3. To design and develop a Power & Reliability Aware Protocol (PoRAP) which consists of three key elements;
    a. *Direct communication*: In a direct communication network, the base station controls the transmissions of sources and no communication between the sources are required. Even though multi-hop communication has often been used in WSNs, there are some scenarios where direct communication between sources and a base station is feasible. As multiple transmissions and receptions are not required in the direct communication, energy savings can be made.
    b. *Adaptive transmission power*: Sending data at higher power tends to produce higher reliability. However beyond a threshold there is little gain in reliability. PoRAP adopts a TPC approach to minimise the transmission power. The key subject is the RSSI-PRR relationship. By keeping operating sensors at an optimal region in the transmission power RSSI graph, power can be saved without compromising reliability.
    c. *Scheduled transmission*: A schedule-based scheme where a time slot is allocated for each source is used by PoRAP. A communication cycle is represented by a

frame which begins with a single control slot followed by multiple data slots. The sources start their radio only for control reception and data transmission. Thus, data collisions and idle listening can be avoided and minimised. Further, clock drift is also studied as it is important in the schedule-based system. Without a proper accommodating strategy, time synchronisation is no longer available and significant energy is wasted on unsuccessful data delivery.

The original contributes lies primarily in the **combination** of direct communication with adaptive power transmission in a schedule based protocol. Direct communication simplifies the design of the adaptive and scheduling aspects of the protocol therebye increasing efficiency.

4. Several experimental studies were conducted to evaluate PoRAP. Feasible indoor and outdoor ranges were explored. The energy efficiency of direct communication was compared to multi-hop communication. Energy savings achievable with power adaptation were quantified. Several RSSI settings were conducted to measure used transmission power and PRR. A 20-source network was used to measure scheduling accuracy. Effects of the duration between two consecutive transmissions were also studied. Finally, PoRAP's performance in terms of power conservation was compared to those of CSMA (Carrier Sense Multiple Access), S-MAC (Sensor-MAC) and B-MAC (Berkeley MAC).
   a. *Estimation of feasible communication ranges*: Feasibility of direct communication is limited by ranges. Estimations of both indoor and outdoor ranges were made by conducting a measurement study and applying its results to an established model.
   b. *Energy savings attributable to direct communication*: Several experiments were set up to study compare direct communication with multi-hop in terms of power consumption.
   c. *Energy savings achievable with power adaptation*: A set of RSSI settings was used to measure the energy savings as a result of transmission power adaptation. Sending at the maximum power is used as a reference. Further, the observed PRR values are calculated. The relationships between RSSI settings, conserved energy and observed reliability were explored.
   d. *Accuracy achieved with scheduling*: Clock drift occurs as a result of uncertainty in the ticking rate. Different local clocks may run at different speeds. Clock drift is crucial in a schedule-based system like PoRAP as it determines the amount of idle listening time required. The clock drifts for multiple sensors were measured and statistical analyses conducted. Median and variation in the drift is also studied to discover how further saving in listening energy can be yielded.
   e. *Comparison of power requirements*: PoRAP's performance in terms of power conservation was compared to those of CSMA, S-MAC and B-MAC. Key

parameter settings from the production habitat and environmental monitoring system, Great Duck Island, such as transmission interval and data payload size were used.

The key contributions here are; to define the range of circumstances for which PoRAP is appropriate, to **quantify** the energy savings that accrue from key aspects of the protocol and to compare its efficiency with other energy aware protocols.

1.6 Methodology

The methodologies used in this study are described in this section. This dissertation reports work which utilises a number of techniques. A survey of existing work on energy aware protocols for WSNs was conducted. Simulations were run to address the proportion of communication energy and the amount of energy saved through transmission power adaptation. Measurement studies were set up to analyse the relationships between link quality metrics and their results influenced the design. The effects of packet size on communication delays were also measured to determine the size of time slots. PoRAP consists of three key elements; direct communication, adaptive power and scheduling. Statistical analyses of the measurements were used to estimate feasible indoor and outdoor ranges. PoRAP's performance is compared to CSMA, S-MAC and B-MAC in terms of energy conservation. The scenario of the production WSNs application, GDI [MPS+02] was used as a benchmark.

1.6.1 Survey of energy aware protocols

A survey of energy aware protocols is important to review the existing work and establish the state of the art in relation to energy aware protocols for WSNs. As sensors are resource constrained, energy conservation should be taken into consideration whilst designing a network protocol. Communication accounts a significant amount of total energy usage. The sensors are switched to different modes of communication such as listening, receiving and sending where a different amount of energy is required [Tmote]. Reducing the amount of wasted energy in each mode is thus a promising approach.

The chosen platform in this work is Tmote sensor platform. It employs the CC2420 transceiver which operates at the range of 2.4GHz. According to [CC2420], it supports programmable transmission power. Thus, adaptive power is feasible in such transceiver. Transmission power control (TPC) scheme benefits from the adaptive power capability. Justification of the adaptation requirement is based upon the measured link quality metrics which are observed at the receiver. Feedback is then required to signal the power adjustment. Lower power can be used especially during good environment.

Wireless sensor networks (WSNs) are a shared medium system where all nodes must engage the medium prior to transmission. Contention occurs if nodes transmit approximately at the same time. Medium Access Control (MAC) protocol is required to resolve contention. Currently, there are two main approaches; contention and schedule based. In contention based, the node senses the medium to check whether there are ongoing activities. It can send if the medium is sensed as free. Otherwise, it backs off and senses the medium again. In schedule based, a time slot is required for each node. It wakes up and sends when the slot arrives. The node is in sleep mode elsewhere to save energy. The selected MAC scheme depends upon the application's requirement. For example, an event based requires the sources to be in active mode most of the time to transmit a large amount of data. On the other hand, the schedule based suits the periodic based application where energy conservation is a major concern.

1.6.2 Simulation

Simulations were used in this work for two purposes. Firstly, the proportion of energy required for communication in WSNs is addressed. If the communication accounts a large amount, it is then worthwhile to decrease the communication energy. Secondly, the amount of saved energy as a result of adaptive transmission power is investigated. The current transceiver such as CC2420 supports the power adjustment which can be conducted via parameter setting in TinyOS command.

TinyOS is an open source operating system for embedded system like WSNs [TOS]. It is widely used in both academic and commercial communities. The simulator used in this work is TOSSIM which is a TinyOS library. The selected release of the simulator is TOSSIM 1 which does not provide power usage measurement capability. PowerTOSSIM, an extension module developed for analysing power consumption of hardware components [SHC+04] is used to address the investigation on power consumption. It is included in TinyOS 1.1.11. The only platform supported in PowerTOSSIM is Mica2 which employed the CC1000 radio chip [CC1000].

PowerTOSSIM includes the required currents which are provided by [CC1000] and other hardware components. The total current is that consumed by all hardware components whilst communication current is that used by the radio. The proportion of communication power with respect to the total can be established. In the case of saved energy by adaptive power, several power settings are made and corresponding current consumptions calculated.

1.6.3 Measurement

There are two measurements which motivate PoRAP design and implementation. Firstly, the relationships between transmission power, distance and link quality metrics, are used for adapting transmission power. Several sensors are located at different locations and they send their packets at various power levels to the base station. Upon packet reception, the base station measures RSSI and LQI. Packet Reception Rate is used as another metric as it is more closely related to the application view. Apart from energy conservation, PoRAP is also aware of reliability. The goal is to minimise communication energy without further reduction in the PRR. The relationships between RSSI, LQI and PRR are important as the network should operate in the region where RSSI produces a high PRR. Lower power can be used without increases in data losses. Beyond a certain point higher power is not helpful as it results in little further increase in PRR.

Secondly, the relationships between communication delays and packet size were studied to establish delay estimation models. Time slot is used in PoRAP and its size must be large enough to cover transmitting and receiving delays. Otherwise, the sources may misunderstand that their slot has arrived and incorrectly initiate transmissions. Data collisions may occur and energy be wasted. In order to establish such relationships, the packet sizes are varied. Several variables are used to store the timestamps conducted at various command calls and event signals. Timers are used for counting the number of ticks and the difference in ticks demonstrates the delays.

1.6.4 Design and development of protocol

In order to test the thesis statement of this dissertation PoRAP was designed and implemented. Direct communication, adaptive transmission power and scheduling are included in PoRAP. It provides efficient data communication in the scenario where the sources communicate with their base station directly. The 50m and 125m indoor and outdoor ranges are specified in [Tmote]. Multiple transmissions and receptions required for message forwarding are not required in the direct communication and a significant amount of energy can be saved.

PoRAP adopts the transmission power control (TPC) scheme. The CC2420 transceiver provides two main capabilities which are useful to the TPC. Firstly, it measures RSSI (Received Signal Strength Indicator) and LQI (Link Quality Indication) during data reception. Both metrics demonstrate link quality. The RSSI measurement is also supported in CC1000. It is linearly related to the transmission power. The RSSI is used in this work to determine whether power adaptation is required. Secondly, adaptive transmission power is provided in the CC2420. The required power can be set in the 5-bit integer format. The CC2420 related component is already provided in TinyOS. It consists of commands for RSSI measurements and power settings.

The base station controls the transmission of its sources in direct communication. The transmission is scheduled. Schedule based approach is adopted in PoRAP where a time slot is allocated for each source. A frame is used to represent a communication cycle in PoRAP. It begins with a control slot followed by several data slots and silent duration to conform the required duty cycle. The source can send only in its slot. It starts the radio for control reception and data transmission. The radio is stopped elsewhere to save energy. Data collision and idle listening are thus avoided and minimised. In order to implement the scheduling, two timers can be used. One is used for timing an active period and another one is for timing a sleeping duration. TinyOS also provides several timer components. The 32KHz timer is used in this work and it generates 32,768 ticks per second or 32 ticks per milli-second. Further, time synchronisation is important in the schedule based system. It is conducted in the MAC layer to exclude the non-deterministic delays which mainly depends upon the capability of hardware and software.

The control packet includes power adaptation notification and scheduling information. Its size is limited by the buffering capacity of the CC2420 which is approximately 117 bytes. In PoRAP, the base station measures the RSSI upon packet reception and compares to the desired range. The notification bits are set to signal power adaptation to the sources. Only two bits are used per source and they support three possible patterns; increase, decrease and retain the current power.

1.6.5 Testing and evaluation

Transmission power adaptation and scheduling were tested to see if they work correctly. A network was set up and the sources start sending at the maximum power. The desired RSSI range consists of minimum and maximum values. The RSSI readings are tracked by the base station. The sources are signaled to adjust their power if the observed RSSI is outside the range. The value of notification bits together with power and corresponding RSSI are monitored by the base station.

The accuracy of scheduling was also tested. The base station allocates a time slot to each of its sources. The transmissions are monitored by the base station. The source ID, number of packet and timestamp at MAC layer are included in data packet. The duration between two consecutive transmissions from the same source is also checked, to see if it is equal the length set by the base station. Moreover, clock drift was also measured in this study. It is important in the schedule based system as time synchronisation is no longer maintained if the drift is not accommodated. Timestamps are conducted by the sources and base station and they are stored in the data payload. The drift is then calculated by the base station. Further, the duration between two consecutive transmissions is varied to determine its effects on the drift. Its variation is also analysed to explore how to further decrease the listening period.

Energy usage in direct communication was compared to that of multi-hop. The effects of distances between nodes and node density were studies. A line topology was used in each experiment to facilitate comparison with previous work. The required transmission power was obtained from the measurement study described previously. This will address the scenario where energy conservation benefits from the direct communication.

An analysis of the parameter space of each protocol was conducted to determine its effects on energy consumption. PoRAP’s performance was compared to CSMA, S-MAC and B-MAC in terms of energy conservation. As PoRAP suits the periodic based application where sensor’s lifetime is a major concern instead of bandwidth utilisation, a scenario of real-world WSNs application should be used in the evaluation. Parameter settings in a habitat and environmental monitoring system, GDI [MPS+02] are used in this study. Further, the methodology in [PHC04] is adopted. An average energy usage per second is chosen as a metric. Further analysis of an active period required by B-MAC for preamble communication and PoRAP for time synchronization is made. It aims for comparison of listening period between contention and schedule based.

1.7 Organisation of Thesis

This section first identifies the key topics addressed in each chapter and then provides an extended introduction to the contents of each chapter.

- **Chapter 2:** The key details of WSNs are described. These include application specific issues, resource constraints and variability in radio frequency. The chapter demonstrates the challenges in protocol development for WSNs.

- **Chapter 3:** Related work is outlined where Medium Access Control (MAC), Transmission Power Control (TPC) and single-hop applications are reviewed.

- **Chapter 4:** Simulation, analysis and experiments were conducted and the results used to motivate PoRAP design and implementation.

- **Chapter 5:** PoRAP design and implementation is described in full. The protocol conserves communication energy without compromising reliability. The RSSI-PRR relationship is used to identify when power adaptation is required.

- **Chapter 6:** The benefits of direct communication, the feasible indoor and outdoor ranges and the evaluation of adaptive transmission and scheduling are addressed. The main objectives are to demonstrate the viability of direct communication and quantitively evaluate the efficiency of communication.

- **Chapter 7:** A comparative study between energy aware protocols is carried out. An analysis of how the parameters affect energy usage is made. The Great Duck Island scenario [MPS+02] and methodology [PHC04] are used for the comparative study.

- **Chapter 8:** Two possible areas of future work are introduced in this chapter. A split frame reduces the risk of control packet corruption and increases the number of supported sources. A multiple base station system makes direct communication possible for a larger area than when the sources are located outside the range of a single base station.

- **Chapter 9:** This chapter concludes the dissertation by providing the key aspects; a summary of the work, the argument summary, the work contribution, the thesis statement and the evaluation of the significance and validity of the thesis statement.

Chapter 2 – Introductory Wireless Sensor Networks

This chapter provides some preliminary details of wireless sensor networks (WSNs) such as their applications, resource constraint issues and variability in radio frequency (RF). At present, WSNs have been used in both military and civil applications. According to the reviewed applications, seven groups are categorised including habitat monitoring (HM) [JOW+02, MPS+02, SMP+04, SPMC04], environmental monitoring (EM) [ALR+06, MPR+05], health monitoring (HEM) [JLR+03, OMSJ06], structural health monitoring (SHM) [CFP+06, KKL+03, PCC+05, SFV05], event detection and tracking (EDT) [ADB+04, BP06, DJD02, NDBC, SBP+04], transport monitoring (TM) [CCV04, Moo04, Nek] and location-aware system (LAS) [BCLP05, IM, R2D05]. Each category has particular characteristics and its own set of requirements. Hence, there are significant challenges in a generic protocol design for a variety of applications. Sensors are scattered in an area of interest and they are activated to conduct their sensing tasks periodically or when an event occurs. Sensor and network lifetimes are a key requirement in the case of periodic-based applications as sensors are expected to operate over a specified duration. Separately, reliability is a major concern in an event-based application. When an event occurs, sensors located in an event area are responsible for reporting data back to the base station. Significant traffic may be generated and injected into the network. Some packets may be dropped or corrupted and the reliability requirement may not be met.

Apart from limited resources, sensors also have constrained communication ranges for indoor and outdoor environments. The distance between the source and destination is crucial to employing an appropriate underlying communication paradigm. Two schemes can be applied to WSNs. A multi-hop approach has been widely used especially when the distance is greater than the communication range. In this scenario, several intermediate nodes are required for forwarding data packets. Each sensor is therefore responsible for communicating with its neighbours in order to determine the path of cheapest power. Such processes require considerable amount of power. A single-hop approach is applicable if sensors are capable of transmitting data to a destination or base station directly. Additional base stations may be scattered over the area in order to serve all the deployed sensors. In this scenario, a sensor does not listen to any signal from its neighbours and the associated energy can be saved.

Radio wave propagation can be considered as electromagnetic radiation. At present RF is widely used in WSNs for data delivery. However, it has uncertainty in its signal. In total two sources of irregularity are categorised including devices and propagation media [ZHKS04]. Radio signal uncertainty is caused by devices including antenna type, transmission power, antenna gains, receiver sensitivity, receiver threshold and the Signal To Noise Ratio (SNR). Those initiated by the propagation media consist of media type, background noise, and several environmental factors such as temperature and obstacles within the media. Apart from the heterogeneity in hardware, WSNs are affected by several environmental factors such as physical barriers and time of day. Effects of climatic conditions depend upon an operating condition. WSNs are not significantly affected by rain, fog and snow as the affected frequencies are higher than the maximum operating frequency of the UHF band [Cla01, McLa97] except a sensor operating at 2.4 GHz which may be affected by fog [Ele]. Similar to wind effects, both humidity and temperature can cause damage to sensors and other electronic devices. Several packaging techniques are available in order to avoid detrimental effects of humidity and water.

In summary, introductory details of WSNs in three subjects; application specific, resource constraint issues and variability in radio frequency are given in this chapter. Wireless sensor networks have been currently deployed in civil applications. Each application has its own set of requirements. One of the main drawbacks is the resource constraint. The power required for all operations is provided by the batteries. Energy conservation should be taken into consideration during protocol design and development. Further, the sensors employ radio frequency for data communication. The signal quality is susceptible to various climatic conditions, physical barriers and time of day. Thus, a measurement based scheme should be used for demonstrating the current link quality.

Chapter 3 – Related Work

In total three subjects are described in this chapter. Firstly, the Medium Access Control (MAC) protocol which is required in wireless sensor networks (WSNs) as they are a shared medium system. The main sources of energy wastage including collision, idle listening, overhearing, overemitting and control packet overhead are described. At present, there are two major schemes which have been proposed for medium access control between nodes. In the contention based approach, nodes sense the medium to detect any ongoing communications prior to starting their own transmissions. If a communication is found, the nodes will back off and sense again. In the case of a schedule based approach, several nodes are allowed to share the channel at a particular frequency. The communication medium is divided into several time slots which are allocated to the nodes.

In WSNs, throughput is important in an event-based application such as a surveillance system. A large number of packets may be delivered to the base station when events such as volcanic eruption or earthquake occur. Each sensor has to be in an active rather than sleep mode and the medium should be engaged by many sensors during such a time. However, periodic-based applications are concerned with battery lifetime. Habitat and environmental monitoring systems are in this category. Sensors periodically collect and send the physical data in periods of minutes or hours. They may be deployed in a remote area where it is costly or impractical to maintain a battery during operation. Hence, energy conservation is more important than throughput. Sensors are switched to sleep mode most of the time to save communication power.

Secondly, the Transmission Power Control (TPC) approach benefits from the programmable transmission power capability in transceivers [CHX+05, JCO05, KKW+03, LZZ+06, SKH04]. According to the reviewed TPC schemes, most of them demonstrate two similar procedures. Firstly, a transmitting node discovers which or how many active neighbours it has by broadcasting messages to them. Secondly, a feedback or acknowledgement system is used after the neighbours have successfully received the messages. Several thresholds are defined to classify the link quality such as received signal strength and each node has additional costs of storing and maintaining the neighbours table. This table should be small due to the resource-constrained nature of a sensor.

The existing TPC schemes focus on multi-hop communication as several intermediate nodes are required for relaying or forwarding a packet to the base station. Once the minimum power for each pair of sensors has been found, it will be used for future transmissions and the path which consumes the least power will be calculated and then used for an end-to-end data delivery. Link quality measurement should not be conducted only once as the radio signal strength may change over time. However, link monitoring frequency requires more power for additional data delivery and computation. An ordinary source or sensor is likely to experience earlier power depletion in the case of too frequent monitoring. Some other research investigates developing or improving lightweight routing protocols for WSNs.

Thirdly, several single-hop applications are reviewed. Direct communication cannot be used mainly because of limited communication ranges. In order to apply the single-hop to a large area, several clusters are created and single-hop may be used in each cluster. An energy balanced protocol for the single-hop is developed in [BP04]. The main goal is to route the packet to an appropriate cluster in order to achieve an equal distribution of workload in terms of communication. The single-hop was used in two major production environmental monitoring systems [MPS+02, MPR+05]. In these applications, the sensors sent the collected every 5 minutes [MPS+02] and 4 hours [MPR+05]. Direct communication occurred in each network patch in [MPS+02] and the collected data was forwarded to the gateway which connected to the Internet. Several algorithms such as sorting [SP03] and reprogramming [PBKM08] have been developed for single-hop WSNs. Both works have the main objective of providing an energy efficient data processing approach. An energy-balanced scheme prevents some sensors from rapidly running out of power in [SP03] whilst reliable data delivery is required in [PBKM08].

In summary, this chapter provides several works which relate to PoRAP development. Several energy conservation approaches have been reviewed. At present, there are two main MAC approaches. In contention based, the medium is sensed to find the ongoing activities. The sensors backoff if the medium is engaged. Otherwise, it transmits the data. A time slot is allocated to each source in the schedule based system. The source sends only when its slot arrives. Thus, the sensor is in sleep mode most of the time. Transmission power control (TPC) benefits from the programmable transmission power in the transceiver. Most of the TPC schemes demonstrate two similar procedures; neighbour discovery and a feedback system. The power is adapted if the observed measure is outside the desired range. Finally, several single-hop applications are reviewed, used mainly in environmental monitoring systems. Further, several algorithms such as sorting and reprogramming have been also developed for direct communication. This demonstrates the feasibility of protocol development for direct communication in WSNs.

Chapter 4 – Motivation for PoRAP Development

The main contribution of PoRAP is to conserve communication energy in WSNs without a further reduction in reliability. This chapter illustrates experimental works and their results which motivate PoRAP design and development. In total six subjects are addressed as follows:

- **The proportion of energy attributed to communication**: Simulations were run to measure the total energy consumed by all hardware components including the radio. The selected simulator is TOSSIM with an extension module, PowerTOSSIM. The goal is to determine whether optimising the communication energy is advantageous.

- **The effects of transmission power adaptation on energy consumption**: Recent transceivers such as CC1000 and CC2420 support adaptive transmission power. The range of feasible power levels depends upon the radio chip. The importance of this study is to quantify the possible energy savings as a result of power adaptation. A lower power can be used for transmission if it produces an effective communication. Another set of simulations was conducted to demonstrate the significance of adaptive power. Some transmission power levels were varied and the corresponding energy was computed. The percentage of saved power based upon the minimum power was obtained.

- **Analysis of existing reception strength prediction models**: Three models are analysed in this chapter; free-space propagation, two-ray ground reflection and shadowing. They have been proposed to estimate the reception strength. There are three main attributes in these models; transmission power, distance and the antenna’s properties such as gain. The models should be used if they take all of the factors such as climatic condition and signal interference into account, otherwise the indices which reflect the current link quality should be measured.

- **Relationship between link quality metrics**: The CC2420 provides RSSI and LQI measurements during data reception. Both metrics are not transparent to the user or application in terms of reliability. The PRR is also used as another metric as it is more closely related to the reliability requirement. The RSSI increases with the power and LQI can be considered as a redundant RSSI [CC2420]. Further, RSSI can be measured in other transceivers such as CC1000. Thus RSSI is used to demonstrate the current link quality. A set of indoor experiments was conducted to establish the relationship between RSSI, LQI and PRR. This relationship is useful to justify whether power adaptation is required.

- **Measurement based**: The effect of environment is not included in the existing models previously analysed in this chapter. In order to conduct power adaptation, the reception strength must reflect the current link quality. An experimental study was conducted to address how transmission power, location, heterogeneity in sensor manufacture and time of day affect the reception strength. They introduce variations in the measurements. Hence, the measurement should be monitored by the base station.

- **Estimation of slot length**: The base station controls the transmission of its sources. No communication between the sources is required as they are not responsible for routing. The schedule based is adopted in this work. The slot must be large enough to cover transmitting and receiving delays. Larger packets require longer delays. The relationship between delays and packet sizes is established. Therefore, the delays can be predicted and the slot size can be selected appropriately.

In summary, this chapter describes simulation, analysis and experimentation which motivate PoRAP design and development. The proportion of energy usage by the radio indicates whether communication energy should be minimised. Transmission energy savings are feasible as the CC2420 supports adaptive transmission power. The RSSI is a selected metric as it can be measured in various radio models. It should be monitored by the base station as variation in the link quality metric is introduced by various factors such as location and time of day. The relationship between RSSI and PRR is useful to justify when power adjustment is required. Finally, the schedule based approach is adopted. The relationship between delays and packet sizes is required to predict the delays. The slot size can be chosen appropriately when the packet size is known.

Chapter 5 – PoRAP Design and Implementation

Details of PoRAP design and implementation are given in this chapter. PoRAP consists of three main features including schedule-based, communication power conservation and link quality monitoring capabilities. The key objective is to conserve energy without further reduction in the PRR. In total five topics are described:

- **Functional requirements**: Four requirements are addressed. Transmission power can be adapted for two reasons. It is supported by the transceiver without an additional hardware requirement. There exists an optimal region where an increase in power does not result in a further increase in PRR. A lower power can be used for transmission without further reduction in PRR. By keeping the network operating in such a region, transmission energy can be saved. As WSNs are a shared medium system, energy wastage in the system should be avoided by adopting the schedule based approach. The sources communicate directly with their base station. The time slotted scheme should support a significant number of sources. Signals to adapt power and scheduling are included in the control packet. The notification should employ a few bits only.

- **PoRAP architecture**: An overview of PoRAP architecture is given. At the top level, it consists of 4 components including a base station, sources, user/application and a sensed phenomenon. Functionalities and interactions between them are described. Each component is then decomposed. There are four main components in the base station and the source; radio, timer, control and memory. The radio makes the node communicate with the other nodes. A timer is required for scheduling. The control masters the components and memory is required for storage. A sensor board is also important for data collection. The interaction between components is depicted to illustrate the flow of command or data.

- **Policies of transmission power adaptation**: An adapted transmission power must be within the available range. The main attribute is the relationship between the RSSI and PRR which is established in Chapter 4. The determination of RSSI bounds can be used in the short-term as the PRR monitoring may take a significant duration. Another policy can be used for the long-term data delivery where the base station is able to count the number of received and transmitted data packets. The link quality changes over time and the RSSI bounds should be amended accordingly.

- **Estimation of communication delays and frame structure**: The measurement of communication delays obtained from Chapter 4 was used to established several models for delay estimation. Linear regression was used and linear equations were obtained. In this study, timestamps were made at command calls, event signals and at the MAC layer. Hence, there are several components to transmitting and receiving delay. These delays are used to determine the length of a slot. Guard length is also determined to accommodate the effects of clock drift. The reserved clock drift is 20 parts per million as suggested in [CMR200].

- **PoRAP implementation**: This section begins with a PoRAP scenario. A frame is used to represent a communication cycle. It begins with a control slot followed by data slots. Each source starts its radio for control reception and data transmission. The radio is stopped elsewhere and the source goes into sleep mode. The source reads the power adaptation notification and scheduling data from the control packet. It adjusts the current power and computes the schedule accordingly. The source stops the radio and waits for its slot to arrive. The radio is stopped again after data transmission. Several components provided by TinyOS are used. Their commands and events are modified to achieve the PoRAP's goals.

In summary, PoRAP aims to conserve communication energy without compromising the reliability in WSNs. An optimal region is important to the justification of transmission power adaptation. Monitoring PRR can be used in long-term data delivery where the base station can count the number of received and transmitted packets. It adopts the schedule based approach where the sources of energy wastage are avoided by allocating a time slot to each source. Several models of delay estimation were established based upon linear regression analyses. The control packet includes the signal of adaptive power and scheduling. Only two bits are used for the adaptation notification. PoRAP consists of several TinyOS components located at the base station and the source. The components are decomposed along with their interactions.

Chapter 6 – PoRAP Energy Conservation Evaluation

This chapter describes PoRAP evaluation in terms of energy conservation and an experiment set up to analyse the energy conservation of the protocol. In total four subjects are addressed as followed:

- **Determination of the feasible communication range of sensors**: PoRAP is specifically developed for direct communication in WSNs. The sources must be located within the communication range of the base station. Otherwise, direct communication is infeasible. In this section, the distance over which direct communication is possible is analysed. The free-space propagation model together with the measurements obtained in Chapter 4 and associated literature [SKPP07] were used. The -95dBm and -85dBm RSSI values were used to obtain the ranges. Significant indoor and outdoor ranges were obtained.

- **Direct communication and multi-hop networks**: A combination of analytical and measurement studies are used to establish the scenarios within which direct communication between a sensor and its base station is possible. These scenarios are then investigated to compare the power demands of multi-hop and direct communication, both for the sensor network as a whole, for regions within the network and for individual nodes. The effects of distance between nodes and densities are also studied. A densely populated network benefits from direct communication as no message forwarding is required. This section demonstrates the viability of direct communication in WSNs.

- **Adaptive power transmission**: PoRAP is an adaptive transmission power protocol allowing lower power to be used for transmission without impacting reliability. This section describes experimental studies which test the power adaptation capability of PoRAP. There are two experiments. The first focuses on testing whether PoRAP correctly adjusts the transmission power and investigates the transmission power required for each cycle. The second experiment investigates the effects of different RSSI settings for PRR and energy consumption. The main objective of the second experiment is to discover the optimal point at which both energy conservation and reliability can be obtained.

- **Scheduled reporting**: PoRAP adopts a schedule-based approach where a slot is allocated to each source. Sources' transmissions are scheduled in order to avoid collisions and minimise idle listening. An evaluation of clock drift is performed. Clock drift is important in the schedule-based approach. It is hardware-dependent and also depends upon the duration between two consecutive transmissions. By knowing the median and the variation of clock drifts, the sources can adjust their schedule and idle listening energy can be preserved. The benefit of schedule versus contention based reporting is discussed as part of the evaluation.

In summary, this chapter evaluates PoRAP performance in terms of energy conservation. In the beginning of this chapter, feasible indoor and outdoor ranges are estimated by determining the free-space propagation models and the measurements. An experiment was conducted to compare energy usage between direct and multi-hop communication. A line topology is used in each study to reflect message forwarding in the multi-hop. Transmission power adaptation is tested. Another experiment focuses on discovering the optimal point by varying the RSSI settings. Clock drift was also measured. It is hardware dependent and non-deterministic. The variation in clock drift is analysed to further decrease the idle listening period.

Chapter 7 – Comparative Evaluation of PoRAP

This chapter describes a comparative study between PoRAP and CSMA, S-MAC and B-MAC in terms of energy consumption. In total three topics are addressed as follows:

- **Overview of compared protocols**: Key details of the protocols are given. Traditional CSMA does not switch the nodes to sleep mode. They have to listen all the time even if there is no packet to send. The hidden node problem is not avoided in CSMA. Sensor MAC (S-MAC) adopts the Request To Send / Clear To Send (RTS/CTS) mechanism to avoid collisions caused by the hidden node problem. S-MAC also provides synchronisation between nodes. An active period is used for control frame exchange along with data transmission and acknowledgement. Berkeley MAC (B-MAC) has been specifically developed for the low duty cycle application such as Great Duck Island [MPS+02]. It uses preamble communication to provide reliable data reception. The preamble length must be at least a check interval. All of these are contention based protocols.

- **Analysis of parameter space**: The main objective of this topic is to investigate how each parameter affects the energy consumption. The chosen metric is an average energy usage per second as in [PHC04]. It is defined as a ratio of total energy consumed by a source to the total number of transmitted data bits in one second. The total amount of energy consumption is the summation of energy used for control packet reception, data packet transmission, listening and sleeping. Each protocol has its own controlling mechanisms. The key parameters include the active period and the exchange of control messages between nodes. Each of the parameters is varied and the corresponding energy consumption is computed.

- **Comparative study**: This study aims to compare the protocol's performances in terms of energy consumption based upon the scenario in GDI [MPS+02]. In GDI, the sources sent every 5 minutes or the sampling period was 300s. The data payload size of 36 bytes was used [PHC04]. An energy usage per second is also calculated. Unlike the other three protocols, PoRAP is schedule based. It suits low duty cycle applications. The number of slots is equal to that of sources. There may be a case where the number of sources is not known in advance. Additional analysis is made to determine the effects of slot usage on energy consumption. Finally, the comparison of required idle listening periods between B-MAC and PoRAP is made.

In summary, this chapter describes the comparative study of energy consumption between the protocols. An overview of the compared protocols; CSMA, S-MAC and B-MAC is given. Each of them has its own controlling mechanisms. For example, an active duration is required in S-MAC for the setup and synchronisation phase whilst a check interval is used in B-MAC for reliable data reception. An analysis of how parameters affect the energy usage is made. The average energy usage is used as a metric [PHC04]. The scenario in GDI [MPS+02] and methodology in [PHC04] are used. The effects of slot usage in PoRAP are also considered. Required idle listening periods between B-MAC and PoRAP are compared.

Chapter 8 –Future Work

Two feasible future works are introduced in this chapter; split frame and multiple base station. Broadcasting a control packet to all connecting sources only once in each frame may generate several issues. Firstly, the number of sources is limited by the limited buffering capacities of the radio unit, which are 128 and 256 bytes for the CC2420 and CC1000 respectively. Secondly, it is feasible for a long control packet to be corrupted during the broadcast. Some sources may inaccurately adapt their current transmission power. Instead of having only one frame which consists of a control slot followed by data slots, an alternative approach, the split frame, is introduced. The control packet size is therefore decreased. Two advantages are recognised; packet corruption can be avoided and the base station can support more sources as the maximum number of sources supported by each control packet is no longer limited by radio's buffering capacity. However, several additional costs are noted. Firstly, the split control packet length is increased as frame identification is required. The sources can check whether the received packet is addressed to them. Additional duration, receiving and clock drift are found to be linearly related to $(p – 1)$ where p is the number of split frames.

The concept of a multiple base station system is also introduced in order to enhance PoRAP's performance. In a large area, some sources may be outside the communication range and direct communication is not feasible. Multiple base stations are scattered over the area to collect data from their sources. Hence, communications between base stations are required. As PoRAP is a schedule-based protocol, the base stations have to agree upon the communication schedules. The master control packet, which includes scheduling information, is broadcast with the base station's attributes. The source-to-base station traffic can be conducted simultaneously in order to minimise the overall duration and associated clock drift. Both radio unit and TinyOS facilitate multi-channel communications, which can be set at compilation time.

In summary, this chapter outlines two possible future works. The split frame approach aims to reduce the risk of control packet corruption and increase the number of supported sources. However, additional costs of communication energy and clock drift are linearly related to $(p – 1)$ where p is the number of split frames. The multiple base station system aims to enhance the current PoRAP's performance in terms of area coverage. Additional communication between base stations is required and can be conducted within different channels to avoid collision.

Chapter 9 –Conclusion

This chapter concludes the dissertation. In total five key aspects are addressed;

- **Summary of work**: The undertaken work and associated methodology are summarised. Prior to protocol development, a survey of energy aware protocols was conducted. Simulations were run in order to investigate the proportion of energy required for communication in WSNs and what amount of energy can be saved as a result of adaptive transmission power. PoRAP consists of three main elements; direct communication, adaptive transmission power and scheduling. It is developed to provide an efficient data communication in single-hop WSNs where the sources communicate directly with their base station. The three main subjects are evaluated; an estimation of feasible indoor and outdoor ranges, the energy savings achievable with transmission power adaptation and a comparative study in terms of energy conservation.

- **Argument précis**: The arguments are summarised and how they relate to existing work are described. Special requirements for protocol development for WSNs; resource constraints and application specific issues are described. The estimation of feasible indoor and outdoor communication ranges demonstrates applicability of direct communication in WSNs. Three studies were conducted where the energy requirements for single and multi-hop communication were compared. A higher transmission energy is required for direct communication but the nodes are not responsible for routing the data to its destination. Intelligent power adaptation and scheduling are included in PoRAP to achieve an efficient data delivery in terms of energy conservation. Finally, a quantification of the energy savings from direct communication, transmission power adaptation and scheduling are conducted.

- **Work contribution**: A description of the contributions of the dissertation is provided. The key contributions include a survey of protocols, an investigation of the relationships between link quality metrics and the design, development and evaluation of the new protocol. Designing a MAC protocol for a class of applications where the goal is energy conservation allows transmission to be optimised with respect to energy usage. The transmission power control (TPC) and schedule based approaches are reviewed and adopted in PoRAP. The RSSI-PRR relationship is used to justify whether power adaptation is required. The goal is to keep the network operating at the optimal region. The sources are often in sleep mode to save communication energy. The viability of direct communication is addressed via an estimation of the feasible communication range, a quantification of the energy savings attributable to direct communication, the communication achievable with power adaptation, the accuracy achieved with scheduling and a comparison of power requirements.

- **Thesis statement**: The thesis statement is demonstrated.

- **Evaluation of significance and validity of the thesis statement**: A critical evaluation of the thesis statement is given and validated against statistical evidence. All of the results demonstrate the validity of the thesis statement. The feasible ranges of the sensors are significant. Adaptive transmission power yields a reduction in transmission energy without unnecessary data losses. Intelligent scheduling demonstrates accuracy in the communication whilst the clock drift is efficiently accommodated. PoRAP is the first power conservation protocol specifically developed for direct communication WSNs.

In summary, this chapter concludes the dissertation. It provides the key aspects which include a summary of the work, the argument précis, the work contribution, the thesis statement and an evaluation of the significance and validity of the thesis statement. A significant amount of work has been conducted in this dissertation. All of the key characteristics of WSNs; power and resource constraints, application specificity, shared medium systems and the variability in link quality are taken into consideration during the design and development processes.

1.8 Conclusion

In this dissertation, an energy conservation protocol, Power & Reliability Aware Protocol (PoRAP), is developed to provide an efficient data delivery in wireless sensor networks (WSNs) where direct communication between sources and base station is feasible. The focused application is periodic-based such as in an environmental monitoring system where energy saving is the major concern. PoRAP has been developed and works most efficiently with a stable set of nodes with limited mobility. It is similar to [EQ07] as scheduling information is included in the control packet. However, clock drift is noted as an important factor which PoRAP accounts but [EQ07] does not. Furthermore, additional message exchanges amongst sensors are not required in PoRAP as the base station periodically broadcasts and is the reference node in the system.

Major contributions of this work include a survey of power aware protocols for WSNs, an investigation of the relationships between RSSI and PRR and the design of the protocol and experimentation. The estimated indoor and outdoor ranges demonstrate that direct communication is possible in a significant proportion of scenarios. In PoRAP the RSSI is measured and monitored by the base station. This is used to determine whether transmission adaptation is required. The results demonstrate that adaptation works correctly. There is an optimal region where power can be conserved without compromising reliability. PoRAP also adopts the schedule-based scheme to avoid collision and minimise idle listening. The clock drift was also analysed in this work. The energy required for idle listening can be further reduced by considering the median and variation in clock drift.

Using the Great Duck Island scenario and parameter settings as in [PHC04], PoRAP consumes less power compared to CSMA, S-MAC and B-MAC. It is less affected by the number of sources than S-MAC and B-MAC as intermediate nodes are not required for data forwarding. Support for multiple base stations will increase the area a patch can cover.

Chapter 2

Wireless Sensor Networks

This chapter discusses some fundamental aspects of wireless sensor network technologies. WSNs (Wireless Sensor Networks) consist of resource-constrained sensors and a base station and they are wirelessly connected. Sensors are powered by tiny batteries and they have to operate on their own without replacement or recharge. Apart from being used in military or surveillance, WSNs have been deployed in several civil applications which have different requirements. Periodic sensing is required in some habitat and environmental monitoring systems whilst event sensing is the norm in surveillance systems. Network lifetime and data reporting rates are therefore major concerns for the former and latter cases, respectively. To be application specific results in a more complicated design process, especially in the case of designing a generic power-aware protocol.

Communication power significantly accounts for power consumption in WSNs. Overhead costs generated by the protocol should be determined. For example, the number of control messages should be minimised. Many works only focus on decreasing the energy used for transmissions as the sources' main function is to report the collected data to the base station. Receiving energy is also important. In some transceivers or radio units such as CC2420, the receiving current is higher than the transmitting current even at the highest power level. Multi-hop has been regarded as an underlying communication paradigm in WSNs as sensors may be scattered over a large area. Direct communication between sources and base station may not be feasible and data forwarding amongst intermediary nodes is thus required. Lower transmission power can be used for shorter distance. However, single-hop can be used when the sources send their data directly to the base station. Additional energy for data forwarding can be conserved. Nodes located near the destination do not risk early energy depletion. In single-hop, the sensors do not listen to incoming routing signals for most of the time. Several Medium Access Control (MAC) protocols have been developed to manage a shared medium and minimise energy used for listening, receiving and transmitting. Data transmissions in single-hop can be scheduled by the base station to avoid data collisions. The sources periodically switch the radios off to save power and wake up when the allocated timeframes arrive.

During data delivery, the data packets are wirelessly delivered and received by the base station. Some link quality indices can be measured by the receiving node. The number of provided indices is dependent upon the radio unit. Radio frequency (RF) is widely used in radio communication. The RF is subject to change in its signal propagation characteristics and strength as a result of any environmental conditions. Hence, the received signal strength should be monitored in order to demonstrate the current link quality.

2.1 Application Specific WSNs

In total, seven groups of applications have been categorised by us based upon their functionalities. Specific capabilities and underlying communication paradigms have been outlined. For example, data encryption may be required in some health monitoring systems for transmitting a patient's diagnosis data to the main server located at the hospital. Furthermore, data correctness is also required in this case. In some applications such as event tracking and detection systems, several intermediate nodes are required for forwarding the sensed data to the base station. However, a direct communication from source to base station is found in some health monitoring systems. This section addresses application specific characteristics of WSNs applications by detailing the differences in their requirements.

Table 2.1 summarises the major characteristics of some WSNs applications. The "Implementation Type" field indicates the type of the application. The following subsections outline each of the remaining fields and some WSN applications are discussed.

2.1.1 Event/periodic based

The "Event/Periodic Based" column demonstrates how often data reporting is conducted. There are three main types including event-based, periodic-based and hybrid. Each sensor is triggered to operate by the occurrence of an event in the case of an event-based application. An example of this application type is the EDT (Event Detection and Tracking). Congestion is one of the major concerns designing a protocol to support event-based networking as it is caused by a lot of traffic generated by all sources in an event area. The key idea of congestion avoidance is to control data reporting rate of such sensors [SAA03]. However, the main assumption is that all data packets have the same priority. Packet loss is therefore tolerantly acceptable. There are several works on congestion control specifically developed for WSNs [EB04, HJB04, LBA+04, WEC03]. The congestion control approach focuses on channel monitoring to dynamically adjust the data forwarding rate. CODA [WEC03] has been designed to cover two types of problems corresponding to the deployed sensors and their data rate. However, it does not provide any queue occupancy monitoring. Sending an ACK (Acknowledgement) in the case of persistent congestion, even if it is small in size, may increase the number of traffic. This mechanism also requires feedback signalling which results in higher cost. Only packet prioritisation could be found in [LBA+04]. However, it proposes the VMS (Velocity Monotonic Scheduling) policy which supports both static and dynamic computation of the requested velocity and it also solves the fairness problem. Both channel and queue occupancy monitoring are provided in [HLB04] and [EB04]. A child node can transmit packets only when its parent does not experience congestion problems and some help from the MAC (Medium Access Control) layer to shift the transmitting time to avoid interference are proposed in [HJB04]. A similar concept also exists in [EB04] by comparing the normalised rate of a node and its parents.

Table 2.1: Summary of major characteristics of WSNs applications

Application	Implementation Type	Event/ Periodic-Based	Mobile/ Static Sources	Single/ Multi-Hop	Requirements				Remarks
					Reliability	Time Sync.	Data Comp.	Data Encrypt.	
1. Habitat Monitoring (HM)									
- GDI [MPS+02], [SPMC04], [SMP+04]	Production	Periodic	Static	Both	N/A	No	No	No	
- ZebraNet [JOW+02]	Experiment	Periodic	Mobile	P2P	N/A	No	No	No	
2. Environmental Monitoring (EM)									
- GlacsWeb [MPR+05]	Experiment	Periodic	Static	Single	Complete	No	No	No	Polling to avoid contention
- Volcano [ALR+06]	Experiment	Periodic	Static	Multi	Complete	No	No	No	Developed own protocol
3. HEalth Monitoring (HEM)									
- WISE [JLR+03]	Experiment	Periodic	Attached to Patient	Single	Complete	No	Yes	Yes	
- WBAN [OMSJ06]	In Design Step	Periodic	Attached to Patient	Single	Complete	No	Yes	Yes	
4. Structural Health Monitoring (SHM)									
- Wisden [CFP+06]	Experiment	Both	Static	Multi	Complete	Yes	Yes	No	Hybrid hop-by-hop and end-to-end data recovery
- SensorScope [SFV05]	Experiment	Both	Static	Multi	Complete	Yes	Yes	No	Complete reliability from sink to source required for reprogramming task
5. Event Detection and Tracking (EDT)									
- Corrosion [BP06]	Production	Event	Static	Mesh	N/A	N/A	N/A	N/A	
- Tsunami [NDBC, NOAA]	Production	Both	Static	Single	Min. 80%	N/A	N/A	N/A	Data transmitted to transducer and forwarded to satellite
- PinPtr [SBP+04]	Experiment	Event	Static	Multi	90%	Yes	N/A	N/A	- Reduce number of nodes on duty - Packet retransmission - Node localisation
- A Line in the sand [ADB+04]	Experiment	Both	Static	Multi	Min. 50% for Classificati on	Yes	N/A	N/A	Developed own protocol
- DSN-CC [DJD02]	Experiment	Both	Both	Multi	N/A	N/A	N/A	N/A	
6. Transport Monitoring (TM)									
- FDOT [TRAF]	Production	Periodic	Static	N/A	N/A	N/A	N/A	N/A	
- Traffic-Dot [CCV04]	Experiment	Periodic	Static	N/A	Complete	Yes	N/A	N/A	Developed own lightweight MAC protocol
7. Location-Aware System (LAS)									
- Cargo Monitoring [MaeRSK]	Production	Periodic	Attached to Cargo	N/A	N/A	N/A	N/A	N/A	Physical location based on GPS parameters
- SmartLOCUS [BCLP05]	Experiment	Periodic	Attached to Object	N/A	N/A	N/A	N/A	N/A	Compute self-location based on neighbours

Each sensor periodically performs its operation. Some examples of data collected by the sensors are temperature and humidity. The significant change in readings may be used to identify the presence of seabirds [MSP+02] and intruders [ADB+04] or it may indicate the occurrence of a tsunami [NDBC, NOAA]. Instead of heavily generated traffics, both sensor and network lifetimes are the core requirement of this application type. Finally, both event and periodic sensing operations may be desired in some applications such as SHM (Structural Health Monitoring) and

EDT systems. For example, the displacement of construction elements is periodically reported for maintenance purposes whilst an event-based operation is applied for warning and evacuating notifications during an earthquake.

This dissertation focuses on developing a power-aware protocol which supports an efficient data delivery in periodic based applications such as health, habitat and environmental monitoring where the data reporting rate is in minutes or hours. Sensors may be scattered over a remote and hostile area to collect and report physical data and they should have to operate for months. Hence, battery lifetime is important and one of the main goals is to conserve communication energy.

2.1.2 Mobility of sources

The mobility of sources or sensors can be found in some particular applications such as HM (Habitat Monitoring, HEM (HEalth Monitoring and LAS (Location-Aware System). In some cases, sensors are attached to the targeted objects [BCLP05, MAERSK] or location [JLR+03, JOW+02, MPR+05] in order to monitor the data of interest or current location. Mobile sensor networks have a different set of supporting infrastructures compared to the traditional WSNs. It is essential for each mobile sensor to know its own location. The GPS (Global Positioning System) is used for locating sensors in [MAERSK]. Alternatively, several nodes with known locations may be used as references for the others to calculate their own locations [BCPL05]. The issues of sensor mobility are beyond the scope of this dissertation.

2.1.3 Single / multi-hop

Wireless sensor networks (WSNs) consist of sensors which are wirelessly connected. The main objective of WSNs development is to collect physical data from an area of interest. Therefore, communication between sensors is a key aspect. Normally there are two node types in WSNs including the source and base station. Sources are ordinary sensors having limited resources whereas base stations are assumed to have more power and other resources. The main duty of sensors is collecting and transmitting data to the destination or base station. The sensors are probably required to cover a large area and direct communication between sources and base station is unlikely due to limited communication range. Several intermediate sensors responsible for forwarding data packets to the base station are therefore required. This is known as multi-hop communication. Each sensor also acts as a routing node in order to find the shortest or cheapest path by means of power consumption. Several applications deploy multi-hop communication such as EM (Environmental Monitoring) [ALR+06], SHM [CFP+06, SFV05] and EDT [DJD02, SBP+04]. The multi-hop approach has several advantages. For example, a new path is discovered when some sensors die. Deploying a large number of cheap sensors over a large area is feasible as the sensors can act as routing nodes and the collected data is forwarded to the destination. However, one of its drawbacks is each node has to listen to the channel most of the time in order to detect if a message is arriving. The sensors have to conduct some computations in order to discover the cheapest path. Moreover, communication with its neighbours is another requirement to set up a selected path. Such processes require a significant amount of power, taken from the battery power available. Introducing several intelligent features to each sensor is also limited due to the power constraint.

Each source can transmit the data directly to the base station if the sources are located within the base station’s communication range. Some examples of existing applications deploying single-hop communication include HM [MPS+02], EM [MPR+05], HEM [JLR+03, OMSJ06] and EDT [NDBC, NOAA]. For single-hop, the sources are located within the base station’s range. Direct communication is therefore feasible and several benefits are realised. One of the advantages is the ability to introduce a variety of intelligent features to the base station as it is assumed to have more power and computational capabilities compared to an ordinary sensor. Each source does not require the power necessary for routing. Idle listening can be minimised as the sources can be switched to sleep mode if they do not transmit data or receive the control packet. The base station controls the communication schedule of its sources to avoid data collisions. Power for carrier sensing is not desired. In multi-hop, each source is responsible for sensing, data reporting and routing. The number of transmissions and receptions increases with the number of intermediary nodes required for data forwarding.

This dissertation looks at protocol development for single-hop. A scenario where the single-hop is viable is Environmental Monitoring (EM). Sources and base stations are distributed and several clusters or patches are formed. A power-aware, single-hop protocol can thus be used in each of the clusters [MPS+02]. A low duty cycle is the norm in EM so the communication cycle of each source can be scheduled by the base station. A time slot is allocated to each source to perform data transmissions. Carrier sensing is thus not required in this scheme. The sources synchronise to the base station by checking the information included in the control packet.

2.1.4 Functional requirements

Different sets of requirements are another key issue in WSNs. Each application may require specifically developed transport protocols [ALR+06]. According to Table 2.1, the “Requirements” field consists of four categories including reliability, time synchronisation, data compression and data encryption. Reliability is described in more details as it relates to the transmission power [LZZ+06, SKH04]. The rest of the categories are also summarised.

A) Reliability

Wireless sensor networks (WSNs) have been currently deployed in several civil applications. The physical data is collected and transmitted for further analysis. The issue of reliability in data delivery is important for providing complete reliability consumes a significant proportion of power. Applying the Transmission Control Protocol (TCP) protocol to WSNs is expensive because of its three-way handshake mechanism and packet header size. UDP (User Datagram Protocol) is considered to be more suitable for sensors although it was designed to provide unreliable data transport. In some applications, data loss may be not a serious problem because of the large amount of deployed sensors. Reliable data transport is important for some types of data such as control messages delivered by the base station [WCK02]. The following paragraphs provide some details of reliable transport protocol for WSNs researches including PSFQ (Pump Slowly, Fetch Quickly) [WCK02], ESRT (Event-to-Sink Reliable Transport) [SAA03], and RMST (Reliable Multi-Segment Transport) [SH03].

One of the main goals to achieve reliable data transport is to orchestrate data receiving and forwarding processes to lessen the packet loss due to buffer overflow. PSFQ proposes three different operations including pump, fetch and report. Data generated from a source node is injected slowly into the network in order to allow such nodes experiencing data loss to fetch the missing packets very aggressively. Timing is a core process in order to avoid operational synchronisation. A hop-by-hop recovery is applied to avoid exponential error accumulation as occurs in the end-to-end scheme. Data delivery status information can be sent back to users or applications in a piggyback fashion.

Focusing only on the forward or sensor-to-sink direction, ESRT was designed to provide a reliable data transport by inspecting current network state in terms of reliability and congestion. The state result is categorised and the reporting frequency is then repetitively adjusted to reach an optimal point. ESRT provides both reliable data transport and congestion control. Local buffer level monitoring is used to detect congestion.

Directed Diffusion [IGEH03] is a routing protocol which provides a multipoint-to-multipoint communication. A sink firstly indicates an interest and propagates it to the nodes. Interest and node information is kept as gradients. The optimised reinforced path is then established to send the attribute-value pairs data. RMST is implemented as a filter to provide some information about the data fragment such as ID and total number of fragments to detect loss. A NACK (Negative ACKnowledgement) is sent via a back-channel to upstream neighbouring nodes in case of data loss.

According to the above fundamental protocol descriptions, several conclusions can be made. In a densely deployed environment, data loss may be accepted. However, this condition may apply only in the case of sensor-to-sink traffic. The sink or base station plays a major role in the network by broadcasting several control packets to the sensors. Such packets should not be lost. Moreover, there are various types of sensing data, such as structural displacement due to wind or earthquake

[XRC+04], which need some combination from different nodes to create usable data before forwarding that data to the sink.. PSFQ designing concepts are more complicated but can be applied to a broader area of application. The data retransmission mechanisms are not mentioned in ESRT as it focuses on statistical reliability. However, PSFQ does not provide congestion control schemes as ESRT does. RMST is designed to run over the Directed Diffusion routing protocol. Although it may take the least effort compared to the other two, it is not generic enough.

B) Other requirements

WSN applications desire more supported features apart from reliable data transport. The required functionality depends upon the application objectives. Discussions on time synchronisation, data compression and data encryption are provided in this part. The time synchronisation is likely to benecessary when the data being collected by various sensors are combined later to yield meaningful results. Some examples of these data are displacements from different sensor nodes [CFP+06, SFV05] and sniper's locations [SBP+04]. The sensed data are processed at the same time to obtain the total displacement at a specific time or location of each sniper. Data compression is one of the power conservation techniques widely implemented in WSNs such as HEM [JLR+03, OMSJ06] and SHM [CFP+06, SFV05]. If delivered data packets are confidential, such as in health monitoring systems (HEM), data encryption is required. Additional functionalities consume more power and power aware schemes are essential to optimise sensor operations and lifetimes.

Apart from energy conservation, reliability is also important in WSNs. Full power can be used for transmissions to ensure that the reliability requirement may be achieved. However, rapid energy depletion tends to occur if the sources keep transmitting at the maximum power all the time. Reliability and power-aware computation can be considered as a trade-off. This dissertation determines how reliability is affected by transmission power level. Recent transceivers support programmable transmission power adaptation. The transmission power produces the received signal strength and can be measured. The relationship between the strength and reliability is studied in this dissertation. The main goal is to transmit at lower power without unnecessary data losses.

2.2 Resource Constraint Issues

This section introduces several issues of resource constraint in wireless sensor networks (WSNs). A sensor can be considered as a small computing device which is capable of sensing, data processing, storage and communication. Sensors are deployed in an area of interest and they may have to operate without maintenance throughout their lifetimes. Power is thus one of the limited resources. Unless an external source of energy is provided, power for all operations comes from batteries. Two AA batteries are required in the widely used platforms such as Tmote, Telos and

Mica. The capacity of the AA battery is approximately 2,000 to 3,000 milli-ampere-hour (mAh). In order to calculate the battery life, the capacity is divided by the actual load current and the obtained lifetime is in hours. An equation for calculating sensor's lifetime is given in [PHC04] where the lifetime is equal to the product between capacity (mAh) and voltage (3V) divided by total energy consumption in micro-joules. The default capacity defined in [PHC04] is set at 2,500mAh.

Communication accounts for a significant proportion of energy consumption. There are four main modes of communication including sending, receiving, sleeping and listening. The transceiver is one of the major sensor components and it makes them capable of communicating with other nodes. Recent transceivers or radio chips such as CC1000 and CC2420 provide programmable transmission power. Sensors consume less power when they send at a lower power level. Hence, transmission power control is one of power-aware schemes in WSNs. The sensors do not always send at the maximum power. Tmote platform is chosen in this study and it employs CC2420 transceiver. For the CC2420 mote the minimum and maximum transmission power is 8.5 and 17.4 milli-amperes (mA). Over 50% of the power can be saved if the minimum power is always used.

Sensors equipped with CC2420 radio chips consume a greater amount of power when they receive data. According to the data sheet, 19.7mA is required for reception. Listening and sleeping consume 365 and 20 micro-amperes (µA), respectively. Hence, in the case of the CC2420 mote, data reception consumes more energy than transmission. The base station is the destination and it may be connected to a desktop or laptop computer. In such cases, the base station has extra power from the connected machine. However, the sensors which act as intermediary nodes between source and destination have to receive and forward packets resulting in sensor's lifetimes being decreased. The listening power is approximately 17 times greater than sleeping. In some applications such as environmental monitoring, the data sampling interval may be in minutes or hours. The transceivers should be switched to sleep mode instead of listening. Scheduling issues occur when two nodes communicate with each other. The data is not received if the receiver is in sleep mode. The nodes have to agree upon the same scheduling. Another scheme based upon contention-based can be used; the receiver can periodically listen to the signal propagated over the medium to inspect whether the incoming message is destined for it.

WSNs are also a shared medium system. Each of the sources and base station has to engage the medium to perform data communication. Data collisions occur if the sources transmit at the same time and energy will be wasted by unsuccessful data delivery. A Medium Access Control (MAC) protocol is required to resolve the contention. The features of the MAC protocol together with the application behaviour determine when a node is idle, when it is listening and when it is sending. As each of these states have different power requirements the MAC protocol impacts upon the efficiency of operation and the power consumption. There are two main MAC schemes; the contention and the schedule based. The medium is sensed prior to transmission and the sensors have to backoff if the medium is declared busy. This dissertation focuses on the single-hop where the sources send data directly to the base station. Another scheme, schedule based, is adopted. A data slot is allocated to each node. No carrier sensing and corresponding energy is required. The main issue is that the slot must be long enough for completing data delivery, otherwise, data collisions are likely. Experimentations required to determine the duration required for both sending and receiving together with the effective factors such as data payload size. Each node is switched to sleep mode to spend the least amount of power when its slot does not arrive.

The buffering capacity of CC2420 is limited to 128 bytes. Taking the header's and footer's sizes into account, the allowable data payload size is thus less than 128 bytes. Apart from sensed data, some control information is required in the packet such as identification and timestamp. Additional packet structures may be required if all the information cannot be stored in one packet. Control overhead is considered as one of the costs and should be minimised in order to decrease transmission and reception energy.

Wireless sensor networks (WSNs) have been currently deployed in several surveillance and civil applications. Sensors may be scattered over an area of interest which can be very large. The communication range is thus important and depends upon the selected transceiver. For example, the CC2420 mote has 50m and 125m indoor and outdoor ranges. Under some circumstances, the maximum transmission power may not produce the maximum ranges. Furthermore, sending data to the node located at farther distances requires higher transmission power. Multi-hop is therefore usually used in WSNs. Several intermediary sensors are required for data forwarding from the source to destination. Single-hop communication is feasible if the destination is located within the source's range. Multiple transmissions and receptions are not required if direct communication applies. However, the same transmission power cannot always be used as the link quality changes over time. The next section describes several sources of variability in radio frequency.

2.3 Variability in Radio Frequency

This section aims at providing an introduction to the radio frequency (RF) which is widely used in WSNs. The variability in its characteristics such as propagation and signal attenuation is also outlined. Generally, the RF behaviour significantly depends upon its operating frequency. Various bands are introduced for standardisation and maintenance purposes. Operating at different frequencies results in different signal characteristics and propagating behaviours. The higher frequency signal tends to travel more straightly and may be reflected by the ground. Finally, losses due to several climatic conditions also differ. Several details given in the following sections are used as a basis for analysing various radio signal behaviours in WSNs.

Sources of variability which affect WSNs are stated in Section 2.3.3. Both physical barriers and some of the climatic conditions affect the signal propagation in WSNs. Furthermore, location and time of day result in fluctuation in the received signal strength even the same transmission power is used.

2.3.1 Radio wave propagation

Radio wave propagation can be considered as an electromagnetic radiation. There are possible four propagating modes including line-of-sight, surface wave, tropospheric scatter and skywave propagations [Cla01]. The signal travels in a straight line in the line-of-sight mode. This occurs when a transceiver is operating at a higher frequency compared to the other three. The distance which the signal can travel is limited by the effect of earth’s curvature. The widely used solution is to place the transmitting device on a tall tower. The remaining three modes are used for signal propagation beyond the horizon. In the case of surface wave propagation, the ground is used as a waveguide and the wavelength directly relates to the degree of diffraction. The diffraction is the angle at which the signal is bent along the earth’s surface. If the signal travels towards the troposphere, it may be reflected. This phenomenon is called troposphere scatter. Finally, the signal is refracted by several layers of the upper atmosphere. The strong ultraviolet emitted from the sun causes ions to be broken and this leads to different densities associated with radiation layers at different altitudes.

2.3.2 Sources of signal variability

At present RF is widely used in WSNs for data delivery. However, it has uncertainty in its signal. There are several experimental studies investigating irregularity in radio signal such as [Dan04], [MCZN05], [Per02] and [ZHKS04]. In total two sources of irregularity are categorised including devices and propagation media [ZHKS04]. Radio signal uncertainty is caused by devices including antenna type, transmission power, antenna gains, receiver sensitivity, receiver threshold and the Signal To Noise Ratio (SNR). Those initiated by the propagation media consist of media type, background noise, and several environmental factors such as temperature and obstacles within the media. Several causes of the radio irregularity are outlined in this subsection.

A) Heterogeneity in devices

This effect can introduce irregularity in radio frequency behaviour. Several causes initiated by devices were observed such as calibration algorithms, antenna orientations, transmitter and receiver orientation, and battery voltage [LLS06]. Linear models describing linear variation amongst different transceivers could not be effectively applied for device calibration and the RSSI (Received Signal Strength Indicator) slightly decreased as the battery voltage declined [MCZN06]. RSSI (Received Signal Strength Indicator) is one of link quality measurements. It indicates the signal strength measured at the receiver side. Normally, it decreases with the increasing distance between the transmitter and receiver [Dan04, MCZN06]. The effects of different sending or transmission powers are discussed in this study.

B) Propagation media

When the signal propagates through a medium, at least one of three effects may occur including reflection, diffraction and scattering. Reflection occurs when an electromagnetic signal encounters an object which is larger than the wavelength. In a rural area, ground is a common source of signal reflection. More sources of reflection are observed when a transmitter is located in an urban area. A variety of surfaces can reflect the radio signal; any building with a metallic surface is a good reflector. When a radio signal encounters an irregular surface such as an object with a sharp edge, diffraction is likely to happen. However, an atmospheric condition can cause diffraction even when the signal is propagated through a free space without any physical barriers. Normally, radio waves travel in a slightly curved path instead of a precisely straight line [McLa97]. Finally, scattering occurs when the electromagnetic wave propagates through a medium which contains a large number of particles smaller than the signal wavelength.

C) Physical barriers

The term “physical barriers” includes both man-made and natural barriers. Several examples of man-made barriers are a table, chair, door, curtain, fence, wall or column. Construction and architectural elements are also in this category. Mountain, hill, tree and forest are considered as natural barriers. These barriers can cause several effects including reflection, diffraction and scattering which were described. According to section 2.3.1, the size of particles and the shape of barriers introduce different effects. The signal will be reflected if it encounters an object whose size of particle is larger than the signal wavelength. On the other hand, the signal can go through that object but scattering may occur.

Temporal physical barriers

Several examples of temporal physical barriers include people and vehicles as their presence varies with time. A link quality measurement during office hours is likely to be less than at night. The strength of the effect is dependent on the density and presence duration. The signal attenuation due to this subcategory is therefore hard to predict. Either maximum or average values may be determined during the protocol design phase.

Non-temporal physical barriers

In opposition to the former subcategory, non-temporal physical barriers do not vary with time and it is less complicated to predict their effects on signal strength. Office furniture and natural barriers are in this subcategory. Trees and forests can also be in this group. The degree of attenuation increases with frequency and relates to the distance which the signal travels. Some interesting attenuation rates as a factor of signal frequency are quoted in [McLa97]. For example, the attenuation rates are 0.1 and 0.3 dB/m (Decibel per metre) at operating frequencies of 500 MHz and 2 GHz (Giga-Hertz), respectively. However, there are a lot of variables involved in accurately considering these effects, such as type of tree. Reflection, diffraction and scattering result in non-isotropic path properties. They are defined as different values when the measurements are conducted along axes in different directions. Therefore, the upper layer protocols may treat this circumstance as asymmetric links. Several impacts of non-isotropic properties to both MAC (Medium Access Control) and routing protocols were investigated by [ZHKS04].

There are a large number of particle types which are built up to form a barrier. There may be a variety of barriers even in one office room. Hence, signal attenuation prediction is difficult. However, most of the non-temporal barriers are likely to be stable in the context of their locations. One of the effective techniques to avoid the effects of non-temporal barriers is to determine the specific locations of each transmitting device in order to obtain the path without signal obstacles [Cla01].

D) Climatic conditions

Climatic conditions greatly affect the radio signal since air is one of the propagation media. The region which the signal travels through is another important aspect. Several atmospheric layers have been categorised according to their altitudes; the troposphere extends to the height of 10km (kilometres), the stratosphere from 10km to 50km, the mesosphere from 50km to 80km, and the thermosphere from 80km upwards [Rad(b)].

Some affecting factors in this category include sun, rain, snow, fog, wind, humidity and temperature. Each of them causes signal attenuation in different ways. Unlike the physical barriers, all of the climatic conditions can be considered as a temporal category. Several experimental results indicate the differences in sensor behaviour in terms of received signal strength between daytime and nighttime even in the indoor environment [LZZ+06, SKH04]. According to the equation proposed by [Dan04], the decrease in signal strength strongly depends upon environment factors. More severe conditions result in a bigger decrease and variation. Two main causes of this result are a weaker line-of-sight signal and stronger influences from signals of other paths. Normally, it takes more effort to predict the signal propagation behaviour in this case. The following describes several effects of each atmospheric factor in more details.

Effects of the sun

At the upper atmospheric layer, an ionosphere is formed by ionisation. The ionisation is caused by high-energy ultraviolet light dissipated from the sun. The higher the altitude, the greater level of ionisation occurs. A large concentration of free ions and electrons can be found in the ionosphere and they affect radio waves. It has significant effects on the radio signal. There are three main layers of ionosphere including the D, E and F regions. The D region spans the altitude between 60km and 90km and can particularly absorb or attenuate low frequency (LF) and medium frequency (MF) radio signals. The higher E region exists at a height between 90km and 140km. It drastically refracts and attenuates the high frequency (HF) radio signals. The F region acts as a good reflector of the HF radio signal and can be found at an altitude between 140km and 400km. The ionosphere is often a reflector for radio signal. A signal with a higher frequency can travel through the lower regions and is reflected by the higher region [Emm06, Rad(c), Spa].

Effects of rain, snow and fog

Several weather conditions can cause signal attenuation. They significantly affect radio signals only when the network is operating in the microwave region. The minimum frequencies which each of these conditions can have effects on attenuation are introduced in [McLa97]. Both fog and snow have noticeable effects when a radio device is operating at a frequency above 30GHz. The signal attenuation due to rain may likely occur at around 10GHz [Cla01]. A noticeable effect is defined as the attenuation of the order of 1 dB or more. Some considerable decrease in radio signal strength (RSS) up to 4 and 14 dBm (Decibel referenced to one Milli-Watt) due to rain and snow storms were observed in [OYB01]. A signal above 2 GHz is significantly attenuated by fog [Ele].

The ITU (International Telecommunication Unit) [ITU] recommends an equation for calculating attenuation due to rain is shown in Equation (2.1).

$$\gamma_r = k R^{\alpha} \tag{2.1}$$

The above equation is valid only for such frequencies up to 40 GHz and path lengths up to 60 km. The attenuation is in dB/km (Decibel per kilometre) where k and α indicate weather and climatic conditions. The R is the rainfall rate in mm/hr (milimetre per hour). Specific frequencies between about 1 and 40 GHz are relatively unaffected by snow, fog and cloud compared to those affected by rain [Cla01].

Effects of humidity and temperature

Those effects from humidity and temperature do not directly apply to the radio signal but the electronic devices such as computers and radio equipments which are very susceptible to them. Several effects caused by these factors are provided in [OYB01] such as errors in data packets and processing and distortion in the output waveform during final stage amplification. A violation in signal propagation is observed when temperature inversion occurs. A temperature inversion is a phenomenon in which a cool air layer is sandwiched between either the Earth’s surface and a warm air layer or two warm air layers. Normally, air temperature decreases with increasing height. The different layers cause changes in refractive qualities and densities. Any UHF signal tends to be refracted back towards earth surface when it hits the edge of warm air layer [Ele].

Effects of other climatic factors

Atmospheric gases are capable of absorbing a radio signal which leads to signal attenuation. The attenuation level due to these effects in a dry atmosphere is less than that in a standard atmosphere in which water vapour is present. According to [Cla01], in the case of frequencies up to 40 GHz, the attenuation is limited to 0.1 dB/km and therefore it is usually ignored. Wind has direct effects on antenna behaviours. The antenna can be shaken and vibrated during the wind storm. As a result, it may be shifted out of a predefined alignment and the propagating signal may travel towards an unintended direction [OYB01].

2.3.3 Radio frequency variability effects on WSNs

A sensor has four main components including a transceiver, sensing, processing, and power unit [KDM05]. The transceiver is the component which is responsible for data transmission and reception. In total three deploying communication schemes are universally used including optical communication (laser), infrared, and radio frequency (RF). Even though it provides high security and consumes less energy than the RF, a laser requires a line-of-sight and is susceptible to atmospheric conditions. The infrared has considerable limitations in its broadcasting capacity.

Unlike the other two, RF requires an antenna for data delivery. There are several widely used commercial transceivers for sensors in a market such as RF Monolithics (www.rfm.com), Ember (www.ember.com) and Chipcon (www.chipcon.com). All of them are designed to operate at the UHF (Ultra-High Frequency) band which spans from 300 to 3,000 Mega-Hertz (MHz) and wavelength of 10 to 100 centimetres (cm) [Rad(a)]. The CC1000 mote operates at 315, 433, 868 and 915 MHz [CC1000] whilst the TR1000 works at 916.5 MHz [RFM]. Both CC2240 and EM2420 operate at 2,400 MHz or 2.4 GHz [CC2420, EM2400]. UHF is suitable for short-range wireless applications and it is also used in television and mobile phone transmissions. The radio signal strength (RSS) based approach is one of the main indices of link quality measurement. It expresses the signal strength in dBm units which is the decibel (dB) expression of power referring to 1 milli-watt (mW) [MCZN06]. Therefore, the higher measured dBm means the higher power.

A) Heterogeneity in hardware and propagation media

At present, the RF is widely used in WSNs for data delivery amongst nodes. However, it has uncertainty in its signal. There are several experimental studies investigating irregularity in radio signal such as [Dan04], [MCZN06], [Per02] and [ZHKS04]. Two sources of irregularity are discussed; devices and propagation media [ZHKS04]. Uncertainties in radio signals caused by devices include antenna type, sending power, antenna gains, receiver sensitivity, receiver threshold and the Signal To Noise Ratio (SNR). On the other hand, those initiated by the propagation media consist of media type, background noise, and several environmental factors such as temperature and obstacles within the media. In conclusion, several effects of hardware and propagation media to WSNs follow the previous discussions for general radio communication case.

B) Physical barriers

Each sensor normally requires a clear path without any obstacles for signal propagation. The presence of physical barriers with various sizes and shapes introduce several path loss effects including reflection, diffraction and scattering. Both reflection and scattering mainly depends upon the size of barriers. The signal tends to be reflected by those whose sizes are larger than the signal wavelength. On the other hand, scattering is likely to occur. Moreover, the operating frequency is another important aspect. For example, the signal propagating from a CC1000 transceiver which operates at 315 MHz tends to be reflected by a larger barrier compared to the same transceiver operating at 915 MHz. A barrier with an irregular shape such as a sharp edge can cause diffraction in signal propagation. The non-temporal physical barriers are static and require less effort to predict path loss. The best way is to place sensors at specific locations where they can clearly communicate to each other. The topology is then known in more detail and the appropriate frequency is finally determined in order to achieve the successful data delivery and minimise the attenuation. Further, the presence of temporal physical barriers such as humans and vehicles can cause additional attenuation.

C) Climatic conditions

The troposphere layer located up to 10km above the ground is likely to affect any frequencies above 30 MHz. A sensor has a transceiver operating at the UHF band which spans between 300 and 3,000 MHz. The operating frequency range of UHF is therefore in the affected region. However, the effects of climatic conditions vary with specific operating frequencies. For example, a sensor operating at lower frequencies is more susceptible to diffraction because of the Earth's surface wave propagation [Cla01]. A sensor operating at 2.4GHz requires line-of-sight (LOS) in order to establish a node-to-node communication. The signal is propagated from a transmitter directly to its receiver. It requires neither reflection from the ionosphere nor ground waves propagation characteristics [Enp]. Moreover, the distance of signal propagation is limited by a power-constrained sensor. Therefore, an ionisation due to the sun in the ionosphere layers does not affect radio propagation in WSNs.

WSNs are not significantly affected by rain, fog and snow as the affected frequencies are higher than the maximum operating frequency of the UHF band [Cla01, McLa97] except the sensor operating at 2.4 GHz which may be affected by fog [Ele]. Moreover, the effects of atmospheric gases can be ignored as the attenuation is limited to 0.1 dB/km. According to the wind effects, they directly vary with the antenna length and the height of transceiver tower. Normally, a longer antenna is required if a transceiver is operating at a lower frequency. The antenna length of a normal sensor may be insignificantly affected by the wind under specific circumstances, especially when sensors are placed on the ground. Wind can cause some damage to the antenna itself and this may result in unavoidable signal propagation problems. Therefore, it may be concluded that wind can cause antenna damages rather than path loss.

Similar to wind effects, both humidity and temperature can cause damages to sensors and other electronic devices. In glacial environment monitoring [MPR+05], failure of sensing nodes were observed due to the presence of water. Several packaging techniques are required in order to avoid such effects of humidity and water. Similar to ordinary electronic devices, sensors may improperly function under high-temperature environments. However, the sensing duration considerably affects signal strength reading at the receiver. This occurs in both indoor and outdoor environments. It is simpler to describe in the case of indoor. In an office building, the density of temporal physical barriers such as humans is smaller at night. Therefore, the signal attenuation is less than the daytime. According to [LZZ+06], the RSSI readings were different hourly and night provided higher signal strengths. This may result from several factors such as temperature, humidity and pressure.

In summary, WSNs are affected by several environmental factors such as physical barriers and time of day. Experiments investigating the effects of some of those sources are conducted in this dissertation. Location also affects the received signal strength. The same transmission power and working environment may not always produce the identical results. Hence, the protocol developed in this dissertation adopts the measurement based approach. A transceiver provides measurements of received signal strength and can be used to demonstrate the current link quality. The strength should not be estimated as false actions may be performed. Some major models are not sufficient as they mainly focus on the distances between sender and receiver [McLa97]. Furthermore, the locations of sensors may not be known in advance. They may be dropped from a plane into a hostile region.

2.4 Conclusion

This chapter has provided several introductory details of WSNs in three main aspects. Firstly, WSNs have been currently deployed in several applications where specific requirements are required for each of them. WSNs are thus considered application specific. Development of communication protocols which can be generally used by some application categories is therefore challenging. Reliability is also important and the application must define a required percentage of successful data deliveries. An increase in reliability often decreases the lifetime as higher transmission power is used.

WSNs are power and resource constrained. Sensors are powered by tiny batteries and their radios operate at low frequencies. Communication consumes a significant proportion of energy. Data transmission and reception consume more energy than listening and sleeping. The main goal in WSNs is to minimise the communication energy which can be achieved by reducing the number of transmissions and receptions whenever possible. This dissertation presents that single-hop can be used in WSNs where direct communication between the sources and the base station are feasible. It can be applied in the network cluster and data forwarding amongst intermediate sensors is not required. Furthermore, the base station controls the communication schedule by adopting the schedule based MAC approach. After control reception, the source sends only when its allocated slot arrives. Carrier sensing in the contention based is not performed and the sources are in sleep mode most of the time. The key issue is to design the slot to have enough length to prevent data collisions.

WSNs use radio communication and the variability in radio signal is crucial. The signal strength is affected by several factors such as physical barrier, distance, location and time of day. The 2.4Ghz radio requires a line-of-sight for signal propagation. Presence of physical barriers may result in unsuccessful data delivery. Transmitting at the same power may not always produce the same received strength. Modern transceivers provide the measurement of received signal strength. The measurement based approach is adopted in this dissertation to demonstrate the current link quality.

Chapter 3

Related Work

Wireless sensor networks (WSNs) enable the distribution of sensors or motes across an area of interest. MEMS (MicroElectroMechanical System) [WP02] have facilitated smaller and cheaper sensors. Now it is economically feasible to place large number of sensors over a geographic area. One example being an island [MPS+02] that was instrumented to obtain physical data such as temperature and humidity. A major constraint on WSNs is their access to power, often sensors are powered through batteries. Replacing the batteries may be costly or impractical. This dissertation examines power conservation within the context of single hop wireless sensor networks. This chapter situates that work within the context of relevant related work. In doing so three types of networks are considered:

- **Single-hop wireless local area networks**: much wireless network communication takes place in these networks. Here we focus on discussing IEEE 802.11. Topologically, these networks are similar to single-hop WSNs.

- **Multi-hop wireless sensor networks**: most WSN research focuses on the multi-hop approach. Within the context of multi-hop communication power conservation is an important priority.

- **Single-hop wireless sensor networks**: these types of networks are closest to the work discussed in the rest of the dissertation.

WSNs are a shared medium system, consequently a Medium Access Control (MAC) protocol is required to resolve contention. The features of the MAC protocol together with the application behaviour determine when a node is idle, when it is listening and when it is sending. As each of these states have different power requirements the MAC protocol impacts upon the operation and power consumption efficiency. There are two main MAC approaches which are respectively contention and schedule based. In a contention system prior to transmission, the medium is sensed to detect whether it is currently engaged. The sources have to backoff if the medium is declared busy. For the schedule based, a time slot is allocated to each source for data transmission. Communication accounts for a significant amount of power. Time synchronisation is an important issue for WSNs to avoid data collisions. Traditional approaches do not suit as they consume much energy and resources. Nodes have to be synchronised with each other and this requires additional message exchanges.

The power level used for a transmission, will affect both the effective range of the transmission and the energy used. Transmission Power Control (TPC) adjusts the transmission power, therebye providing a means to both control energy consumption and transmission range. On a multi-hop wireless network for TPC to work a transmitting node needs to become aware of the nodes it can transmit to and the transmission power required for each node. This may be obtained through broadcast packets and acknowledgments. When direct communication between a node and a base station is possible, single-hop WSNs are feasible. In a large area, several clusters can be established where packets are routed between clusters and single-hop communication takes place within a cluster.

3.1 Medium Access Control Protocol for WSNs

This section aims to describe the details of the Medium Access Control (MAC) protocol which is required for both wireless and wireless sensor networks as they are both categorised as a shared medium system. MAC provides shared medium allocation and contention avoidance. The main goal is to minimise the communication energy which is constrained in both networks, especially when the nodes are battery powered. Communication accounts for a significant proportion of energy usage. Battery replacement and recharge are sometimes costly and impractical. Reducing energy wastage in the shared medium system is therefore important. However, additional control messages and the corresponding energy are required. Four main sources of energy wastage in the shared medium system are described as follows:

- **Collision:** may occur when some nodes are trying to send approximately at the same time. The messages theoretically travel at the speed of light ($3 * 10^8$ m/s) in the medium they are in and they can collide. No data is therefore received at the destination and energy is wasted. Data retransmissions are performed and it means that additional energy will be used.

- **Idle listening:** the nodes may have to listen to the incoming signals most of the time. Idle listening is important especially in the multi-hop network where data forwarding is required amongst intermediary nodes. A duty cycle is used to periodically put the nodes in an active mode when they have to communicate with the others. The required data reporting interval in WSNs may be in minutes [MPS+02, TPS+05]. The sources can be switched to sleep mode if they do not transmit.

- **Overhearing:** the nodes may overhear and receive any packets which are not destined for them. This problem is feasible when the hidden nodes overhear the sender’s signal and the intended receiver is outside the hidden nodes’ communication ranges.

- **Overemitting:** occurs when the receiving nodes are sometimes not ready to receive the messages. In this case, sleep latency is important and the required duty cycle may not be achieved as additional duration is required for the retransmissions. Hence, it is necessary to orchestrate communication between senders and receivers.

- **Control packet overhead:** additional information or controlling packets are required to achieve the protocol's objectives. The control packet overhead is also important in WSNs as the sensors have limited resources. Additional communications consume more power than transmitting or receiving larger packets.

At present, there are two major schemes which have been proposed for medium access control between nodes. Contention and schedule based approaches are adopted or enhanced to support specific requirements. In the contention based approach, nodes sense the medium to detect any ongoing communications prior to starting their own transmissions. If a communication is found, the nodes will back off and sense again. In the case of a schedule based approach, several nodes are allowed to share the channel at a particular frequency. The communication medium is divided into several time slots which are allocated to the nodes.

An efficient media allocation is also required by some applications where throughput is the major requirement. The destination requires a specific number of received packets within a time period. For example, in WSNs, throughput is important in the event-based application such as a surveillance system. A large number of packets may be delivered to the base station when events such as volcanic eruption or earthquake occur. Each sensor has to be in an active rather than sleep mode and the medium should be engaged by many sensors during such a time.

Periodic-based applications are mainly concerned with lifetime of the battery. Habitat and environmental monitoring systems are in this category. Sensors periodically collect and send the physical data in periods of minutes or hours. They may be deployed in a remote area which is costly or impractical to maintain during operation. Hence, energy conservation is more important than throughput. Sensors are switched to sleep mode most of the time to save communication power. One feasible difference between habitat and environmental monitoring is that sensors are fixed at specific locations in the case of the environmental system. Additional features are required for the mobile WSNs such as localisation as the sensors may have to report themselves to the new base station or neighbours.

This dissertation focuses on the periodic-based WSNs applications where the sensors always stay at their locations. Such a scenario is thus suitable for the environmental monitoring system where energy conservation is the key concern to prolong the sensor's lifetime. Power & Reliability Aware Protocol (PoRAP) has been developed and supports a fixed set of nodes. PoRAP adopts the schedule based scheme in order to resolve the contention in the shared medium. The base station controls data transmissions of its sensors. It broadcasts a packet and the sensors know when they can transmit their own packets. Only one channel is used for control and data transmissions. Data communication is represented by a frame where it consists of a control slot followed by data slots. A sensor can send only when its allocated slot arrive so data collisions are avoided and the radio is turned off to minimise idle listening.

3.1.1 Ongoing communications detection and collision avoidance

A) Contention-based

Radio communication is considered as a shared medium. Simultaneous transmissions cause collisions and some energy will be wasted. The nodes should transmit at different times. As each of them does not know when the others send, a random access approach can be used. ALOHA is one of the random access protocols for radio communications [Nbr70]. There are two key approaches. The first one is pure ALOHA which is simpler and does not require synchronisation amongst nodes. They send without waiting for the beginning of the slot. Slotted ALOHA is an improvement in terms of channel utilisation. Time is divided into several equal sized slots. The node sends at the beginning of the next slot when it has data to send. Collision is therefore still possible and retransmission is required.

ALOHA has been regarded as a fundamental technique for the multiple access communication and is the basis of later protocol developments which include Carrier Sense Multiple Access (CSMA). The medium is sensed prior to transmissions. There are two main extended CSMA approaches including Collision Detection (CD) and Collision Avoidance (CA). The main goals are, respectively, to prevent collision and eliminate ongoing collision. For CSMA/CD, collision detection methods are dependent upon the underlying medium. In the case of Ethernet or wired Local Area Network (LAN), the senders compare the transmitted with the received data. Collision is declared if the transmitted data differs from the received. The node which detects collision overlays the signal which caused the collision and it immediately terminates its transmissions. A jam signal is sent to the other senders and there is an exponential random backoff performed. Such an approach will decrease the collision probability in the future transmissions. However, CSMA/CD does not suit wireless LAN and WSNs. The main reason is that the nodes may turn themselves to sleep mode after transmission to save power. Furthermore, additional communications notifying the collision detection requires more power from the resource-constrained wireless nodes.

Several existing schemes for wireless LAN and WSNs are developed based upon CSMA with Collision Avoidance (CA). Data transmission is randomly delayed if the medium is declared busy. Otherwise, the data is sent. Such a mechanism avoids possible data collisions caused by the nodes located within the communication range. However, there is an important case where two senders are located outside the range and they cannot hear each other. Collisions occur at the receiver if they transmit at the same time. CSMA/CA cannot protect the hidden node problem. IEEE 802.11 implements Request To Send (RTS) and Clear To Send (CTS) and they are used for transmission detection and handshaking between sender and receiver [Erg02]. The RTS is sent when the node has a packet to transmit. The receiver responds to the request by sending the CTS when it is ready for data reception. The hidden node problem is avoided by not responding to the RTS. After the RTS-CTS handshaking is completed, data and acknowledgement communications are conducted. The other nodes have to wait until these activities are completed.

Once the medium is declared busy, the nodes backoff for a particular interval and the medium is sensed again. According to [Erg02], five timing durations are defined in IEEE 802.11. They are used for timing RTS, CTS, DATA and Acknowledgement (ACK) frames. The interframe spaces are used by access control protocols including the Point Coordination Function (PCF) and Distributed Coordination Function (DCF). The PCF is centralised whilst the DCF is a distributed scheme. The basic 802.11 MAC protocol is DCF based upon CSMA. Short Interframe Space (SIFS) is the shortest interval followed by a time slot. When the destination receives the RTS and it is ready to receive the data, a CTS frame is sent after the SIFS duration is ended. After the CTS reception, the transmitter waits for a SIFS interval and sends the Data. Furthermore, the SIFS is used before an ACK transmission at the receiver.

Priority Interframe Space (PIFS) and Distributed Interframe Space (DIFS) are equal to a SIFS plus one and two time slots, respectively. The PIFS is used instead of SIFS in the case of the PCF approach. Even if the channel is declared free, the node has to keep sensing the channel for an additional random time. The total sensing period prior to transmission is defined as DIFS. Extended Interframe Space (EIFS) is the longest and it is used when the MAC layer receives a frame containing an error. The EIFS allows the nodes to complete the frame exchange correctly before the new transmission is initiated.

The waiting interval is obtained by calculating the Network Allocation Vector (NAV) which is considered as a virtual carrier sensing mechanism. The NAV is set when transmissions are detected in the channel which is in use during the DIFS interval. Nodes have to wait until the NAV is reset to zero to initiate their own transmissions. In order to provide fairness amongst nodes, MAC selects a back-off value and increments the retry counter. The back-off is decremented each time the medium is declared free for one time slot duration. The contention window is doubled and a new back-off interval is chosen if collision occurs.

The RTS and CTS are adopted and enhanced in several works [PRC05, QCJS03, JV02, LMT04, HVB01, YHE03, DL03]. In [JV02], the RTS and CTS frames are sent at full transmission power to increase the reception rate. Transmission power is adapted to conserve energy and causes an asymmetric link. Therefore collisions may occur as transmission range is changed and the hidden node problem is incurred. Moreover, the duration of current transmission is included in the RTS/CTS duration field and it can be accessed by the nodes located within the range.

Apart from the estimated durations required by ongoing communications, the RTS and CTS frames include a transmission rate which is based upon the Signal to Noise Ratio (SNR) of the received frame [LMT04]. In [HVB01], the packet size is also stored in the RTS and CTS in order to allow a pair of nodes to agree on a transmission rate. The number of RTS retries is set to two in [DL03]. Furthermore, there may be a case where a node goes to sleep too early whilst its neighbours still have more data to send. The Future RTS (FRTS) is implemented to inform the receiver about more data transmissions. It is also used to indicate busy channel.

Traditional mechanisms are provided by CSMA in WSNs [DL03, YHE03]. The B-MAC (Berkeley MAC) protocol implements a Clear Channel Assessment (CCA) in order to detect ongoing communications in the medium [PHC04]. Base noise is measured when the channel is free, for example immediately after data transmission or reception. Variations in signal strength during a clear channel are found to be higher and may contain outliers. A higher and more stable signal strength indicates ongoing data receptions. So a higher signal strength may not always indicate that the channel is being used. B-MAC checks for an outlier to test the channel availability. The channel is declared clear if an outlier is detected. Otherwise, ongoing transmissions are addressed if five samplings are taken and no outlier is found.

B) Schedule-based

Instead of using carrier sensing, another MAC protocol approach, based upon the schedule-based schema, can be used. The main concept is to reserve a time slot for all the sensors. At a specific frequency, the signal is divided into several time slots. A slot is thus allocated for each node. A node is only able to send at a specific time and collisions can be therefore avoided. This approach suits the friendly scenario where the number of sensors is static. Furthermore, the sensors can switch their radios off and turn to sleep mode whilst the others are sending and idle listening is thus minimised. There are concerns with this scheme. Firstly, time synchronisation amongst nodes is required as they have to agree upon the same schedule. Additional communications are required for local time exchanges. Each sensor consists of an oscillator which generates ticks and they represent the local clock. The clocks run at different speed and clock drift may occur. The drift is important as it can be accumulated into a significant amount of time and time synchronisation cannot be maintained. Sensors will then transmit simultaneously and collisions will occur at the base station.

The Cambridge Ring (CR) is a closed wire loop, local communication system which connects several machines together and forms them into a ring topology [Nee79, KM82]. Application areas which require small to medium bandwidth such as peripheral sharing and file transfer are suitable for the CR deployment [HN98]. The slotted base approach employed in the CR supports collision avoidance as a station is not capable of transmitting if the slot contains information. When a station has data to send to the other node, it copies the data stored in its storage unit into an empty slot. It also writes its address in the source address field. The destination address is assigned and it will be checked by the stations connected to the ring when the slot arrives at each station. During slot circulation, another station may require to transmit its data. It determines whether there is an empty slot to copy its data into.

There are several main design issues. Firstly, each slot should be long enough to contain the information. Essential control bits are also taken into account in order to support an efficient data delivery. The transmission speed of the medium affects the frame length. The Cambridge Ring supports the system with a raw data rate of 10 megabits per second. Secondly, the number of slots in a frame should be traded off in order to provide fairness amongst stations. In the case of one slot per frame, the other stations must wait until the destination receives the information and the frame is marked as available. Thirdly, the reliability is also essential for achieving an application's requirement. Two approaches are considered in [Nee79]. The retransmission may be employed along with the negative acknowledgement (NACK). This scheme may not be suitable in some systems where resources limitation is important. Timeout-based may be used to trigger the retransmission if the sender does not hear from its receiver. Under some circumstances, a degree of packet loss may be acceptable in some applications. Hence, retransmission may not be required.

Traffic-Adaptive Medium Access Protocol (TRAMA) is specifically developed for WSNs [ROG03]. It assumes a single and time-slotted channel used for data and control transmissions. The random-access slots are used for controlling whilst the scheduled-access ones are used for data transmissions. A sensor exchanges its traffic information or schedule which is in a bitmap format with its neighbours. Such information includes a set of receiving nodes and bitmap length is equal to the number of one-hop neighbours. Hence, each sensor advertises its schedule before starting data transmission. The schedule should be consistent and updated periodically. Furthermore, the two-hop topology information across all nodes is obtained based upon the traffic information propagation. Transmitter and receiver are chosen by determining the schedule and two-hop topology in order to avoid collision.

SEA-MAC has been developed for environmental monitoring WSNs where the sources periodically collect the data [EQ07]. It also supports a low duty cycle application. By assuming that the sensing schedule is known in advance, the base station recognises and maintains the synchronisation. The packet includes the duration left for the next listening period, the length of listening period and the length of sleeping period. Upon receiving the scheduling information, sensors disseminate the packets to their neighbours. The nodes keep their radios on unless they receive the synchronisation packets. However, carrier sensing is also used in SEA-MAC prior to packet transmissions. Clock drift is not taken into account in SEA-MAC.

C) Medium access control for single-hop WSNs

Direct communications between sources and base station are feasible in the single-hop. Both contention and schedule based can be implemented. There are several concerns in the protocol development as WSNs are application specific. High throughput and reliability are crucial in the event-based whilst lifetime is important in the periodic-based WSNs. This dissertation focuses on developing a power-aware protocol for the single-hop and periodic-based WSNs.

Wi-Fi (Wireless Fidelity) is the specific name provided by the Wi-Fi Alliance to the IEEE 802.11 standards for Wireless Local Area Network (WLAN). Wi-Fi is the most common shared medium MAC. Wi-Fi supports single-hop communication and is concerned with maximising throughput and reliability. It also has to handle a large number of nodes which are dynamically joining and leaving the network. In the context of WSNs requirements, Wi-Fi is more suitable for event-based systems such as surveillance and structural health monitoring applications.

The schedule-based approach suits the single-hop WSNs for several reasons. Firstly, all sources or sensors send their data to the base station. Carrier sensing is not essential as their transmissions can be scheduled and controlled by the base station. Secondly, idle listening can be minimised in the single-hop as the sources are not responsible for routing. The single-hop can be used in the cluster which consists of a base station and several sources. Only one channel is sufficient for both control and data transmissions. This dissertation aims to develop a protocol for the periodic-based WSNs. Prolonging lifetime is the major goal.

Both [ROG03] and [EQ07] are schedule-based and they have been developed for multi-hop WSNs. Wi-Fi is IEEE 802.11 based and it aims at high throughput and reliability. Therefore, it is possible to have a different MAC protocol which has different properties and works more efficiently for the single-hop and periodic-based WSNs.

3.1.2 Duty cycle and idle listening minimisation

This section aims to describe the determination of duty cycle and idle listening minimisation in several existing MAC protocols for WSNs. Duty cycle is defined as a ratio of waking up duration to the total interval which includes sleeping. The waking up period includes the durations required for listening, receiving and transmitting. Traditional networks such as ad-hoc wireless networks and wireless local area networks (WLANs) require high throughput or efficient bandwidth utilisation. Nodes in such networks have to be in the active mode most of the time for data transmissions. Minimising idle listening to conserve power is not therefore the main goal. Determination of duty cycle in the schedule-based MAC approach is inherently simpler than the contention-based where it is sometimes not clear when the radio can be switched off. In the schedule-based schemes, the key issue is time synchronisation and timing. If the overhead for those can be kept low, then an efficient scheme should be possible.

As WSNs are application specific, duty cycle and idle listening minimisation requirements are dependent upon applications. High duty cycle is essential in event-based applications such as an intrusion detection system. The sensors deployed to detect the events have to be in an active mode more frequently. In order to achieve the high throughput during a short period of time, the sensors may have to be active most of the time and idle listening minimisation may not be the main goal. Environmental monitoring WSNs consist of sensors which may report their readings every minute or hour [MPS+02, TPS+05]. For example, the work described in [PHC04] was designed to achieve a 1% duty cycle which is required in [MPS+02]. A sensor should be switched to sleep mode if it has no data to transmit or receive. Most of the reviewed approaches are inspired by the multi-hop where each sensor is responsible for routing [PHC04, YHE03, DL03, ROG03, EEDP04, LKR07, JBT03]. It is therefore necessary to listen to the signals from its neighbours. The authors of [YHE03] quote some results from previous studies which state that idle listening consumes a significant amount of power especially when the listening period is long. It is recommended that the sensors must avoid idle listening by periodically being switched to sleep mode but delay may become another key concern [Haa04].

In the contention-based approach, listening is required for carrier sensing or orchestrating between nodes. Carrier sensing is performed prior to transmission to avoid collisions. Additional listening is required in [PHC04] to guarantee reliable data reception. If no packet is received within a predefined timeout, the sensors are switched back to sleep mode. Preamble length must be at least as long as the sampling period. This scheme puts the high cost to the receiver as it has to listen and receive the preamble longer. It was designed for the low duty cycle WSNs. Each sensor periodically exchanges its schedule with its neighbours in [YHE03]. Neighbour discovery is thus important and synchronisation between sensors is desired. Each sensor has to maintain a table which stores the schedules of its neighbours. This scheme aims to decrease the carrier sensing interval but additional resources are required. Moreover, Request To Send (RTS) and Clear To Send (CTS) are exchanged prior to data transmissions. It suits the periodic-based applications as several message exchanges are performed. This work was enhanced to support the heavy traffic systems where communication delay becomes important by allowing the overhearing nodes to wake up for a short period at the end of transmissions. This lets the neighbours forward data to the listening nodes immediately. Both [YHE03] and [PHC04] have been widely used in the periodic-based WSNs. This dissertation also develops a schedule-based protocol for this application category. This will be used in a comparative study which is discussed later in this dissertation.

The authors of [DL03] demonstrate the minor impacts of collision, protocol overhead and overhearing on energy consumption compared to idle listening. Idle listening is reduced by transmitting all messages in burst. The durations between bursts are variable. In order to determine the length of the active period, an interval variable is used to specify the minimal amount of idle listening per frame. The sensors will be switched to sleep mode if no event is detected within such an interval. Buffer capacity is used to determine an upper bound of maximal time frame as messages between active periods have to be buffered. This work suggests the interval to be 1.5 times the combination of contention duration, RTS length and turn-around time. Asymmetric communication in a unidirectional communication pattern, such as sensor-to-sink, may cause an early sleeping problem as a node may go into a sleep mode when its neighbours still have messages to send. An additional frame is used to let another node know that there is a message for it and also that the medium is currently used by the other nodes. Furthermore, a sensor with a full buffer may require to send out data instead of receiving. Therefore, it immediately sends its own RTS to another node instead of replying with the CTS.

A hardware-software codesign platform has been proposed for a single-channel contention protocol based upon nonpersistent CSMA [EEDP04]. This scheme mitigates the idle listening by combining nonpersistent CSMA with preamble sampling. In nonpersistent CSMA, a node has to wait for a random duration prior to transmission after a free medium has been detected. The preamble sampling is conducted to check for activities in the channel such as transmissions by means of received signal strength. A wake-up preamble signal prior to data transmission helps to avoid overemitting. The length of a wake-up preamble is decreased by learning from the sampling schedule of direct neighbours. Each sensor updates its sampling schedule during every data exchange by piggybacking the remaining time until the next sampling. Additional information is included in the acknowledgement. This concept may not be efficient if there are many neighbours as each sensor has to keep and maintain a table where the schedules are stored.

Three side effects of low duty cycle have been observed in [LKR07]. Firstly, latency is increased as the sender may have to wait until the receiver wakes up. Secondly, a fixed duty cycle may lead to an inefficient data delivery. For example, a duty cycle for the highest traffic load results in a significant energy waste. However, a duty cycle for a low traffic load results in low throughput and a long queuing delay. Finally, a fixed synchronous duty cycle may increase the possibility of a collision. DMAC is built based upon the time-slot concept. It solves such problems by assigning an offset to the active/sleep schedule of each sensor. The offset is related to the depth on the tree which is assumed to remain unchanged. The idea is to sequentially wake the nodes up like a chain reaction. The packets can be thus continuously forwarded to their destinations. Both receiving and sending durations have the same length which is enough for one packet transmission and reception.

The determination of the duty cycle is simpler in the schedule-based approach as the communications can be scheduled in advance. The sensors wake up by periodically switching their radios on for control receptions and data transmissions. Control and data can be sent in the same or separate communication channel. A time slot is allocated to each of the sensors for transmissions and they switch the radios off and turn to sleep mode whilst the others are sending. Idle listening can be minimised as sensors are in sleep mode most of the time. However, a high duty cycle is difficult to achieve in the schedule-based approach. For a set of fixed sensors, each of them has to wait until the others finish their transmissions. Throughput observed at the base station may be reduced as some sensors are not able to send a specific number of packets within a period of time. However, the contention-based approach can support the systems which require heavy traffic as the sensors send at anytime the medium is free. The schedule-based supports power conservation via idle listening minimisation.

3.1.3 Time-synchronisation protocol

Time synchronisation is crucial in a schedule based protocol as the nodes have to agree upon and follow the predefined schedule. A reference node is required to synchronise the nodes. Time synchronisation in an order of microseconds may be required in WSNs. The Network Time Protocol (NTP) which is used in the Internet does not suit wireless sensor networks due to its resource constraint [EGE02, GKS03]. An external system that behaves like a timing reference such as a Global Positioning System (GPS) may not be available in some areas. Each sensor has an oscillator which generates ticks and they are used to represent the local clock. Different local clocks may run at different speeds and clock drift can occur. The drift can be accumulated into seconds and the synchronization deteriorates. Hence, clock drift should be monitored in a schedule-based protocol design.

Several non-deterministic delays in data communication and processing such as send, access and receive delays are determined in [EGE02]. Some delays are hardware dependent and these non-deterministic delays are discarded. The remaining delays, which are taken into account, are propagation and reception. Physical-layer broadcasts are used to periodically deliver the messages which are not included in explicit timestamps. It assumes that insignificant variability in the propagation delays is observed at such receivers. Receivers use the packet's arrival time as a reference for comparing their local clocks and they exchange such measurements and the offsets are then computed. More accurate results will be obtained if the message reception is tight and if the receiver is able to measure its local time of reception promptly. However, a sequence of reference messages from the same sender is preferred. Once clock offset and skew are estimated, a table storing parameters which relate to offset and skew with respect to every other clock in the network is maintained by each node. In multi-hop, a third node is required for synchronising two nodes which are located within different neighbourhoods.

In a sender-receiver based scenario, the synchronisation is conducted at the receiver [GKS03]. Two phases are desired. Firstly, each node assigns itself a level to form a spanning tree. A root node is assigned to level 0. It broadcasts a message to its neighbours. Upon reception, other nodes assign level which is one greater than the level included in the message. The message will be discarded if the level is already set. Secondly, pair-wise synchronisation is performed and it is started from the root node. Prior to the synchronisation, the root node broadcasts a packet. The nodes at lower level respond by sending a packet to the root node. Acknowledgement will be transmitted and the exchange of local times is completed. The same processes will be repeated to create a network-wide synchronisation. In [GKS03], the receiver synchronises to the sender. Both clock drift and two-way propagation delay are computed by the receiver. The timestamps are performed at the MAC layer. In order to avoid collisions, several random backoffs are used prior to transmissions.

Instead of forming a spanning tree, an ad hoc structure is formed and the global time maintained by the root node is transferred to the nodes [MKSL04]. The cost of the tree establishment is not therefore required. The protocol provides a network-wide synchronisation by knowing the difference between the estimated global time at the root and the local time at the receiver. The clock offset is computed at the receiver. Only a single broadcasted message is sufficient to establish synchronisation between a sender and some receivers. In addition to timestamping at the MAC layer, several delays required for completing data transmission and reception are considered in order to minimise the source of synchronisation errors. The message broadcast from the root node consists of preamble, SYNC bytes, message descriptor, actual data and CRC bytes. Such information enables message reassembling with correct byte alignment and message verification. The associated durations are used to adjust the timestamps. Interrupt handling and encoding/decoding times are taken into account by normalising the timestamps. Multiple timestamps are thus obtained but only the final error correction will be included in the message. Clock drifts were measured in order to develop an estimate model to predict the drift of the receiver clock with respect to the sender clock. The model was obtained from running the off-line linear regression.

Unlike [EGE02], time synchronisation in the single-hop WSNs can be performed at the sources and the base station is a reference. Comparing to [GKS03], the base station is at level 0 whilst the sources are at level 1. A cluster consists of a base station and several sources which are located within the base station's communication range. The local clock exchange in [MKSL04] can be used. A broadcast control packet, including scheduling information, is sufficient for the synchronisation. Timestamping at the MAC layer also applies as the non-deterministic delays are eliminated. The sources do not compute the clock offset. They schedule their communications by considering the included information.

3.1.4 Summary

WSNs are a shared-medium system where medium access control is required in order to avoid data collision. There are two major schemes including contention and schedule based. Both of them have been adopted and enhanced for WSNs which are considered application specific. Environmental monitoring systems normally require a low duty cycle. Sensors should be switched to sleep mode when they have no data to send in order to minimise idle listening. In the case of contention-based, additional control frames, apart from RTS and CTS, are proposed to achieve the application's energy requirements. A time slot is allocated for each sensor in the schedule-based approach. Collision and idle listening can be thus avoided and minimised. The reviewed schemes are developed for multi-hop WSNs.

PoRAP is categorised as a schedule based approach. It has been developed to support WSNs where direct communication between sensors, or sources, and base station is feasible. Unlike [ROG03], the same channel is required for control and data transmissions. Furthermore, scheduling information is included in the broadcast control message as in [EQ07]. However, PoRAP does not perform carrier sensing prior to transmission and clock drifts were measured. In the context of time synchronisation, the sensors synchronise to their base station via control packet reception. Unlike [EGE02], no exchange of local clock offsets amongst sensors is required. The sensors located within the base station's communication range are at the same level and they report to the base station. Timestamps are performed at the MAC layer in order to avoid non-deterministic delays as in [MKSL04].

3.2 Transmission Power Control

Communication accounts for a significant amount of power. Reduction in data size and number of data communications is useful but it does not take the radio susceptibility to physical and environmental factors into account. The main concept of the Transmission Power Control (TPC) is to adjust transmission power of a sensor with respect to varying link quality. A sensor has limited resources such as power and communication range. Moreover, WSNs are sometimes deployed in a very large area where direct communication between sources and base station is not always feasible. Therefore, data communication in WSNs is often multi-hop. However, single-hop can be used in WSNs where the sources are able to communicate with their base station directly such as the network patch in [MPS+02]. The transmission power used by the source is varied based upon the current link quality. According to the reviewed TPC approaches for both wireless and wireless sensor networks, two similar procedures are observed. Firstly, a transmitting node discovers how many active neighbours it is connected to by broadcasting messages. Secondly, a feedback or acknowledgement system is used after broadcast message reception. The adaptation policy is applied based upon the received feedback.

3.2.1 Neighbours discovery

Each sensor has to know neighbours located in its communication range. Topology may change as new nodes are deployed and some nodes may no longer function. It is thus necessary to periodically discover active neighbours. There are two main schemes to detection including broadcasting messages and obtaining the topology from the routing protocol. Alternatively, a beacon is broadcast for the discovery [EKCD00, ESWW00, JCO05, LZZ+06]. The maximum power level is used by each sensor for the broadcast [EKCD00]. Two distributed schemes were specifically designed for mobile multi-hop wireless networks [RRH00]. The transmission power is adjusted in order to maintain the topology or number of neighbours. Additional overheads, due to controlling mechanisms, are not necessary as they use locally available neighbour information from routing protocols.

Developing algorithms which are capable of adapting transmission power with respect to an actual link quality is the inspiration of [KKW+03]. The solutions based upon global knowledge of network condition do not suit the resource-constraint WSNs. Each sensor uses the same transmission power level for sending packets to all of its neighbours. Algorithms were designed to integrate with routing protocols with per-node power level information. A power-aware routing protocol called Real-Time Power-Aware Routing Protocol (RPAR) is proposed in [CHX+05]. It was specifically designed for real-time applications in which several circumstances such as communication delays or packet deadlines are crucial. Two main features are dynamic transmission power adaptation and a routing decision in order to minimise the miss ratios. Neighbour discovery starts with broadcasting a Request To Route (RTR) packet. The forwarding policy takes several factors including one-hop delay and packet forwarding progress into account.

Neighbour discovery is simpler in the single-hop scenario as the sources report to their base station and they are not responsible for routing. The base station broadcasts its control packet to all sources located within its range. In this dissertation, it is assumed that the base station has extra power which may be obtained from the connected desktop or laptop computer. According to this scheme, the table storing the neighbours' information is not required by each source. Moreover, a set of fixed sources is considered. The base station takes control of the same sources through the entire operation.

3.2.2 Feedback and power adaptation

Several measurements such as RSSI (Received Signal Strength Indication) and LQI (Link Quality Indicator) are used for the feedback mechanism to let the transmitting node know the current link quality and the power required to reach its destination node. Both RSSI and LQI demonstrate the radio signal quality of each message and can be measured at the receiver. Generally, RSSI is a measurement of signal power of an incoming packet whereas LQI is the measurement of the "chip error rate" and is more closely connected to the SNR (Signal to Noise Ratio). The SNR is a ratio of received signal power to the background noise level. The latest transceiver such as CC2420 [CC2420] and EM2420 [EM2420] having an operating frequency around 2.4 Giga-Hertz (GHz) providing LQI readings whilst the older model such as CC1000 [CC1000] and TR1000 [RFM] does not. Moreover, the PRR (Packet Reception Rate) may be used to describe link quality [SKH04, LZZ+06, SDTL06].

Apart from the beacon, several messages can be used to demonstrate the current link quality. In [KKW+03], life messages are used for feedback. The sender counts the number of reachable neighbours at a particular transmission power. If the number of received acknowledgements is less than a predefined threshold, the sender will increase its power by a certain factor. Alternatively, the number of receiver's neighbours is added to the life acknowledgement packet. After the sender receives the acknowledgements from its neighbours, it calculates an average of the number of its neighbours' neighbours. Thus, the sender knows its neighbour connectivity to other nodes. The routing protocol, RPAR described in [CHX+05], determines energy consumption of all forwarding choices which meet the urgency requirement. A delay estimator computes the delay by monitoring the link quality and the contention delay. A neighbourhood manager is responsible for finding an energy-efficient forwarding choice which achieves the delay requirements. The counter of the selected forwarding choice is incremented and decremented for the others. The choice with the smallest counter is evicted when the table is full and the new entry is inserted. A multiplicative increase and linear decrease approach is used for power adaptation.

There are two main objectives in [SKH04] including investigating behaviours of low-power wireless communication links with respect to varied transmission power under different settings and proposing a new scheme on power control capable of removing low quality links. The required link quality is indicated by a threshold value which is the minimum Packet Reception Rate (PRR) for maintaining a good link. A link with different quality in each direction is defined as asymmetric link. Regarding the proposed algorithms, each node firstly measures the quality of each link by determining the PRR at various transmission power levels. In order to set a threshold value for the required link reliability, an optimal unicast transmission power for each link is set. The threshold will be set to the minimum value of the observed PRR if the PRR is greater than the threshold. Otherwise, it is set to the maximum transmission power.

Another threshold, the blacklist threshold, is set to consider whether a link can be converted to a good link. If not, that link is blacklisted and no longer used. Two levels of blacklisting are proposed including link-based and packet-based. The latter specifically supports different applications and packet types. Finally, the broadcast transmission power of an interested sensor is selected from the maximum unicast transmission power assigned in the two previous steps. This assures that a sensor transmits broadcast packets at a power level which is strong enough to reach all of its neighbours. Moreover, all good links are guaranteed. Offering both link-based and packet-based blacklisting supports a variety of packet types and applications. However, it is specifically designed to run with the Directed Diffusion routing protocol and no additional experiments with the others were conducted.

The main goal in [JCO05] is to keep the number of neighbours within a desired range. Both RSS (Radio Signal Strength) and PRR were chosen as metrics. The PRR does not require any special hardware support but it has a software overhead in order to maintain a neighbour table. Therefore, the RSS is chosen as a key metric as it can be measured by the radio hardware. The mechanism starts with a node transmitting a beacon message. A receiving node with a good link quality records the ID of the sender. The list of the IDs will be piggybacked onto the beacon message when the receiving node has its own message to send. Finally, a node knows the number of its neighbours by determining its ID in the incoming messages. The number of neighbours is then compared to the predefined value and the transmission power control mechanism is applied to achieve the goal. The transmission power will be increased if the observed number of neighbours is less than the predefined value. The algorithm is capable of reducing the degree of adjustment as the number of neighbours converges to the targeted value.

A linear relationship between the transmission power and RSSI was observed in [LZZ+06]. Different transmission powers were required to maintain the value of RSSI measurements. This implies that wireless link quality changes and power adaptation is a promising approach to achieve the required RSSI. Moreover, both RSSI and LQI readings were plotted against PRR. Significant variations were found and were caused by fading, background noise and instability in radio hardware functionality. In order to assign a minimum and workable transmission power to each communication link, ATPC was designed based on the concept of changing a pairwise transmission power level over time. As a result, each node assigns a different minimum transmission power for each link. The two main ideas behind its design is a neighbour table, which is maintained by each node, and a closed loop for transmission power control which runs between each pair of sensors. The entries of the table include Node ID, proper transmission power levels defined as the minimum power which provides a good link quality, and several parameters used for linear predictive models of transmission power control. The closed loop feedback is used to obtain the minimum transmission power by gradually adjusting the power.

A predictive model is used to estimate the RSSI distribution at various transmission power levels. An idea of a predictive model is to employ a function in order to approximate the RSSI distribution at various transmission power levels. After obtaining several pairs of data, a linear curve-fitting approach is then used. Two constants are solved by the proposed equation. Upon receiving the beacons, the neighbours measure both RSSI and LQI values. They send these values back to the transmitting node as a feedback. Note that the predictive model is initially used to estimate the proper power level only. Power level variation is then conducted for each pair of nodes to monitor the real link conditions.

After the initialisation process, a sensor looks up the generated table when it has data to send. An actual link quality can be obtained after the receiver sends both RSSI and LQI values back to the transmitter. A link quality monitor module decides whether a notification message is necessary. The main duty of this module is to monitor the link quality and generate a notification only when the link quality is below the desired level or the current signal is too high. Upon the notification reception, the transmitter adjusts the proper transmission power.

All of the reviewed TPC works were developed for the multi-hop. The main reason is the limited communication range. Direct communication may require a higher power compared to those between hops but multiple transmissions and receptions are not required in each communication path. The relationship between transmission power and RSSI observed in [LZZ+06] indicates that power adaptation can be used to achieve the successful data delivery. This is feasible as the RSSI also relates to the PRR. The feedback mechanism can be adopted in the single-hop as the indices demonstrate the current link quality. Notification of power adaptation in the single-hop is included in the control packet. The adapted power of each source may not be included in the control packet due to the limited buffering capacity of the radio. Few bits should be used instead to inform the source to increase, decrease or retain the current transmission power.

3.2.3 Summary

According to the reviewed transmission power control schemes, most of them demonstrate two similar procedures. Firstly, a transmitting node discovers which or how many active neighbours it has by broadcasting messages. Secondly, a feedback or acknowledgement system is used after the neighbours successfully receive the messages. Several thresholds are defined to classify the link quality and each node has additional costs on storing and maintaining the neighbours table. This table should be small due to the resource-constrained nature of sensors. Knowing the environmental factors may help to select an appropriate power level accurately and quickly. Moreover, the speed of convergence to the optimal transmission power is another concern as more power will be wasted on useless adjusting operation cycles. Further, the transmission power control should not depend upon any specific routing protocols. The existing schemes focus on multi-hop communication as several intermediate nodes are required for packet forwarding to the destination. Once the minimum power for each sensor pair has been found, it will be used for future transmissions and the path which consumes the least power will be calculated and then used for an end-to-end data delivery. Link quality measurement should not be conducted only once as it may change over time.

PoRAP adopts the transmission power control (TPC) scheme to reduce transmission energy by adapting the transmission power. Neighbour discovery by means of routing is not included in the PoRAP as it is not dedicated to multi-hop WSNs. A table storing link quality index for each pair of sensors is not required in PoRAP. The base station communicates with its sensors directly and message exchanges amongst sensors are not thus desired. PoRAP takes advantage of the received strength that can be read during data reception like [JCO05, LZZ+06]. The PRR is also considered as PoRAP supports probabilistic reliability requirement. The relationships between RSSI, LQI and PRR are also determined in PoRAP. Reduced transmission power should not result in lower than required reliability. The RSSI is used as the main metric reflecting the current link quality as it is supported by the CC1000 and CC2420 transceivers. Being related to the RSSI, the LQI can be used to estimate the PRR [SL06]. In PoRAP, a control message is broadcast by the base station and it also includes the notification of transmission power adaptation based upon RSSI measurements.

3.3 Single-hop Application in WSNs

This section aims at providing several details of applying single-hop approaches to wireless sensor networks (WSNs). The single-hop cannot be used mainly because of limited communication ranges. In order to apply the single-hop to large area, several clusters are created and single-hop may be used in each cluster. An energy balanced protocol for the single-hop is developed in [BP04]. The protocol provides an optimal routing by determining four primitives which includes the number of packets, the number of nodes and the maximum numbers of packets that can be transmitted and received by each node. There are two phases of data routing. Firstly, the packet is routed to the suitable cluster which contains the destination node and secondly, the packet is redistributed within the cluster in single-hop. The packets will be routed in order to achieve an equal distribution of workload in terms of communication. Rapid energy depletion at some nodes can be thus avoided. Another communication channel via additional radio or frequency is required for controlling. All nodes are synchronised during communications to avoid data collisions. Moreover, the protocol adopts Request To Send (RTS) and Clear To Send (CTS) to achieve collision avoidance. Both frames are used to indicate that the nodes still function. Transmit, Receive and ShutDown are categorised as three communication modes. In terms of energy consumption, it is assumed that Transmit and Receive consume the same amount of energy whilst energy usage during ShutDown is negligible.

Single-hop was also used in [MPR+05] which is a production glacial monitoring WSNs. The sensors were located within the ice and collected data such as temperature, strain and pressure every 4 hours for 15 seconds. The base station was programmed to directly communicate with its sensors only once a day for maximum 15 minutes. In order to improve transmission of data through the ice, the communication frequency was decreased twofold. Firstly, the frequency of 433 mega-hertz (MHz) was selected instead of 868 MHz and secondly, larger antenna was used. The sensors communicated with the base station via polling mechanism. The authors point out several advantages of such a scheme such as reduced duty cycle, no overhead and collisions. However, deployment of new sensors may be complicated. According to the results, several problems were observed. Firstly, 4 out of 7 sensors failed to transmit data. This is mainly because some sensors were moved as a result of the sub-glacial movement. The sensors were thus outside the communication range. Moreover, some sensors died due to immense stress of the ice or short circuits as a result of water. Some data collection was missing as the sensors and the base station were no longer synchronised. The base station broadcast a packet to the sensors to adjust their clocks every day during the 15-minute window. The Global Positioning System (GPS) time was used as a timing reference. This implies that more frequent synchronisation is required as clock drift is accumulated over time.

Apart from the glacial monitoring, the single-hop could be used in the Great Duck Island (GDI) which is a production habitat monitoring [MPS+02]. The sensors were deployed on the island to collect some environmental data which indicates the presence of seabirds. A duty cycle of approximately 1% is required and the targeted lifetime is 9 months. The system is divided into three tiers. A network cluster consists of sensors which send the data to the master node. The processed data is then forwarded to the gateway which is linked to the server which connects to the Internet. Single-hop can be used in each communication patch. Furthermore, transmissions can be scheduled as a low duty cycle is desired. The number of slots may be equal to that of sources. One communication channel is sufficient for both control and data communications. However, an additional channel is required for the communication between base stations for collision avoidance. The single-hop also applies in [TPS+05] which is an environmental monitoring system. The sources, attached at different locations on a tree, send the data directly to the base station. Like [MPS+02], approximately 1% duty cycle is required by [TPS+05]. The sources reported their readings every 5 minutes.

Several algorithms such as sorting [SP03] and reprogramming [PBKM08] have been developed for single-hop WSNs. Both works have the main objective of providing an energy efficient data processing approach. A single-hop, and time-synchronised WSN is assumed in [SP03]. Moreover, transmission and reception energy consumption is assumed to be equal. The sensors are periodically switched off. No energy is used whilst the sensors are in sleep mode. The remaining power of each sensor is sorted to find the maximum value. The sensor which owns the highest remaining power will be assigned to report data in the next transmissions. An energy-balanced scheme prevents some sensors from rapidly running out of power which may result in making the whole network non-functional. Several sorting algorithms have been developed to support uniform energy dissipation amongst the sensors and balanced energy consumption.

Reliable data delivery is important in reprogramming the sensors [PBKM08]. New code or amendment to the existing code may be required during the sensor's lifetime. A program image may be large compared to low bandwidth radio communication. The code should be delivered in an efficient way to avoid both redundant traffics and retransmissions. Thus, minimum resources should be consumed by the network reprogramming. Practical experience from an existing multi-hop water pollution monitoring system is a driving force for developing a single-hop reprogramming scheme where only one node within the network is reprogrammed. The multi-hop results in high reprogramming costs, especially when the link quality is low as multiple retransmissions are required. The single-hop is more suitable when the link is unreliable and linear or approximately linear topology is used. A dual reprogramming protocol was developed where the single or multi-hop will be chosen based upon current network conditions.

3.4 Conclusion

This chapter has provided several works which relate to PoRAP development. Power and resource constraint is one of the main drawbacks of wireless sensor networks (WSNs). Several energy conservation approaches have been reviewed. WSNs are a shared medium system where the medium has to be free prior to initiating transmissions to avoid data collisions. Medium Access Control (MAC) consists of two main schemes, contention and schedule based. The medium is tested to see if it is currently engaged prior to transmission. The sensor has to backoff if the medium is declared busy. Otherwise, it is able to send. However, hidden node problems cannot be eliminated when two or more sending nodes cannot hear each other. Collisions are likely at the receiver located between them. Additional exchange of frames such as Request To Send (RTS) and Clear To Send (CTS) are used in the IEEE 802.11 and this mechanism is adopted in several contention based protocols.

For the schedule based protocol, a time slot is allocated to each source for data transmission. The source wakes up by turning its radio on for data transmission when its slot arrives. Otherwise, it is in sleep mode most of the time and idle listening can be thus decreased. As sensors have to agree upon the same schedule, time synchronisation is important in the schedule based system. Each sensor consists of an oscillator that generates ticks and they can be considered as local clock. In the multi-hop, sensors have to exchange timing information. A timestamp is supported by an operating system for WSNs such as TinyOS which is used in this dissertation. A reference node has to be established to let the other nodes synchronise with it. Additional power is thus required for the synchronisation.

PoRAP is a schedule based protocol specifically developed for single-hop WSNs. Data communication is represented by a frame which includes a control slot followed by several data slots. A channel is used for controlling and data transmissions. PoRAP is similar to [EQ07] as scheduling information is included in the control packet. However, clock drift is noted as an important factor but not determined in [EQ07] whilst it was measured in PoRAP. Furthermore, additional message exchanges amongst sensors are not required in PoRAP as the base station periodically broadcasts and is the reference node in the system. Time synchronisation refers to the timestamps performed at the MAC layer in order to eliminate several non-deterministic delays which mainly depend upon processing speed and operating system interrupt [MKSL04].

Selected transmission power affects both the effective transmission range and energy consumption. Transmission Power Control (TPC) adjusts the transmission power by looking at the link quality measurements. Several existing TPC schemes hold two common phases. Each source discovers its neighbours by initially broadcasting a message at the full transmission capacity. The receivers then acknowledge the message and the sender measures the received signal strength. Lower transmission power will be used in these cycles. A table storing the minimum power for each neighbour is thus required. Received Signal Strength Indicator (RSSI) and Link Quality Indication (LQI) measurements are provided by the CC2420 transceiver whilst only RSSI is supported by the lower frequency CC1000 radio. Both of these metrics can be obtained during data reception and they are related to the Packet Reception Rate (PRR).

PoRAP benefits from the relationships between RSSI, LQI and PRR to discover the best point to operate the network at. The RSSI is used as an indicator reflecting the current link quality. According to the RSSI-PRR relationship observed in [LZZ+06], the PRR steeply increases with the RSSI until stability is reached. The curve is too steep at the beginning to accurately predict the PRR outcome at a given RSSI value. The relationship between RSSI and PRR will be discussed in more details later in this dissertation. Moreover, given the variability of interference it would not be able to make a guarantee on the probabilistic reliability. In the context of TPC, PoRAP is close to [LZZ+06] which is specifically developed for multi-hop WSNs. Both of them use RSSI as a feedback of link quality and decide whether notification of transmission power adaptation is required. Moreover, the maximum power level is initially used for the first transmission. The differences between PoRAP and [LZZ+06] are that PoRAP does not require the neighbour table for each node. Furthermore, the notification is always included in the broadcasted control packet for PoRAP whilst additional message is required for [LZZ+06].

The single-hop approach is used in several scenarios such as routing, environmental monitoring and reprogramming. Multiple transmissions and receptions can be eliminated if the sources can communicate with their base station directly. In a large area, several clusters can be established where packets are routed between clusters. PoRAP can be used to support single-hop communication within each cluster.

Chapter 4

Motivation of PoRAP Development

In this chapter, the results of experimental investigations into how a protocol aimed at single-hop wireless sensor networks (WSNs) may minimise the rate of power usage are presented. Simulation results demonstrate significant effects of power adaptation on power usage and the benefits of direct communication where listening to other sensors is not necessary. Experimental results indicate that transmission power, location, heterogeneity in sensor manufacture and time of day are four key factors introducing variations in link quality. The metrics indicate whether the transmission power adaptation is desired to support power conservation. Notification of power adaptation is broadcast during the control phase and the sources conduct the adjustment prior to transmission. Time synchronisation between sources and base station is crucial in a time-slot based protocol. Sending and receiving delays are linearly related to the packet sizes whereas the two-way propagation delay is significantly small. Determination of slot length can be estimated and message transmissions should therefore be scheduled with respect to the sending and receiving events occurring at the Medium Access Control (MAC) layer.

4.1 Introduction

In this chapter important issues for the conservation of power for wireless sensor networks (WSNs) are identified and related to the design of communication protocols. The ability to do real-time data collection from both hostile and friendly environments without communication lines makes WSNs an interesting research area. Resource constraint and application specific conditions have to be catered for during the communication protocol development. Different set of requirements are required by different applications. Chapter 2 points out two main categories of WSNs applications including the periodic and the event based. Sensors periodically send their readings in the periodic based whilst heavy traffic are generated during event detection in the event based. Three main requirements in communication protocol development for WSNs are addressed as follows:

- **Lifetime or throughput as a main goal:** In the periodic-based scenario, sensors are sometimes deployed in a remote area and have to operate on their own throughout the targeted lifetime and data reporting rate is fairly constant. Power conservation is therefore important as the sensors may be expected to run for several months. Instead of achieving a longer lifetime, some applications focus on how to make the base station receive the desired number of packet receptions. Throughput is thus a major concern in the event-based application.

- **Duty cycle:** The required duty cycle is mainly concerned about the amount of generated traffic at a specific time. In a surveillance system, many readings may be collected from a site and sent within a short duration. Hence the sensors have to be often in an active mode for communications. However, the sensors switch their radios off more often in an environmental monitoring system. Current temperature and humidity may be read every minute [MPS+02, TPS+05]. A lower duty cycle is desired in such cases and the sensors can be in sleep mode most of the time.

- **Amendment to the locations of sensors:** The sensors are either fixed at specific locations or moved. Mobility of sensors is crucial for network routing. In a fixed topology, the same communication route can be assumed if all of the nodes are still performing. A new path has to be discovered if the nodes are moved. Localisation is another key issue if the sensors are attached to objects, such as in the local-aware or habitat monitoring system.

This dissertation aims at building a communication protocol for WSNs. The targeted scenario is the periodic-based where a low duty cycle is required. The network consists of a fixed set of sources and a base station. Furthermore, direct data communications between the base station and its sources are feasible. The communication protocol to be developed will effectively support the single-hop WSNs. Such a structure forms a network cluster which can be used in some environmental or habitat monitoring system such as [MPS+02] and [TPS+05]. As the number of sources is fixed throughout the communications, the data reporting rate is fairly constant. The communication of the sources can be therefore scheduled and controlled by the base station. A time slot is allocated to each source and will be used for data communication. Only one source can use the shared medium whilst the others switch to sleep mode by turning their radios off and consuming the least amount of energy. Data collision can be avoided and idle listening can be minimised.

In order to develop a protocol to support the described scenario, several questions arise as follows:

- **Of the total energy consumed by a sensor node, how much of it is attributed to communication?** If communication accounts for a high proportion of a sensor's total energy budget, then optimising energy consumption for communication is itself important.

- **How does the energy used for communication change at different transmission powers?** A significant difference in energy consumption at different transmission power levels would motivate adapting the power used for transmission to the minimum required for effective communication.

- **What factors affect signal reception and provides the basis for determining whether the models discussed are good predictors for sensor network communication.** If the important factors affecting the receiving signal strength are not included in the existing models, the indices reflecting the current link quality should be measured.

- **What metrics should be used to measure the signal strength?** The relationship between the metrics can justify whether the transmission power adaptation is desired to support power conservation.

- **Are measurements required to determine the power required for effective communication?** Experimental results indicate that transmission power, location, heterogeneity in sensor manufacture and time of day are four key factors introducing variations in link quality.

- **Can scheduling be done with sufficient accuracy to save energy when compared to a contention based approach?** There are two main approaches which resolve contention in the shared medium system. In this dissertation, the single-hop topology is assumed to remain unchanged. The schedule-based protocol is adopted to schedule the communications. The slot length can be accurately estimated if the relationship between delays and packet sizes are addressed. The two-way propagation delay should be significantly small as data travels at the speed of light.

4.2 Sensor Node Power Consumption

This section establishes the significance of network communication as a consumer of energy within a wireless sensor network. In doing so a careful reading of sensor data sheets is used to inform calculations based upon the sensor's parameters and simulations. What proportion of the power is used for communication is investigated and how power may be conserved is identified.

In order to investigate how power is consumed by a sensor, a simulation study has been established. The results are validated by the CC1000 transceiver data sheet [CC1000]. As the sensor operating system used in this dissertation is TinyOS, the selected simulator is TOSSIM which is a TinyOS library. TinyOS is an operating system specifically designed for embedded devices such as sensors [TOS]. It has been widely used in both research and commercial communities. The selected release of the simulator is TOSSIM 1 and it does not provide power usage measurement capability. PowerTOSSIM, an extension module developed for analysing power consumption of hardware components [SHC+04] is used to address the investigation on power consumption and it is included in Tiny 1.1.11. The only sensor platform supported in PowerTOSSIM is Mica2 which employed the CC1000 radio chip [CC1000]. The PowerTOSSIM supports an operating frequency of 400 Megahertz (MHz) and a voltage of 3 Volt. The energy model file of PowerTOSSIM adopts the required transmission current for each power level from [CC1000]. According to [CC1000], 31 output power levels ranging from -20 to +10 dBm can be programmed. The dBm is the measurement of power loss in decibels (dB) using 1 milli-watt (mW) as a reference value.

4.2.1 Simulation parameters

A sensor node was created in the simulation and performs as a transmitting node. An experiment was conducted to obtain the current consumption required by each transmission power level. In total five transmission powers including -20, -10, 0, +6 and +10 dBm were used. The corresponding current consumption was measured by [SHC+04] and their results are shown in Table 4.1. A simulation duration of 60 seconds and a total of 30 runs were conducted at each power level. A higher current will be consumed if the sensor transmits at a higher power.

Table 4.1: Current consumption measured by [SHC+04]

Transmission Power (dBm)	Required Current (mA)
-20	5.21
-10	6.10
0	8.47
+6	13.77
+10	21.48

4.2.2 Simulation results

The results shown in Table 4.1 were used to compute the energy consumption required by each transmission power level. Figure 4.1 shows error-bar plots of radio and total energy consumption at -20, -10, 0, +6 and +10 dBm. An analysis of power usage and conservation with respect to the maximum power level is described in Table 4.2.

According to Figure 4.1, several observations can be made. Firstly, an increase in transmission power results in a higher energy consumption. Transmitting data at lower power uses less energy. For example, over 75% of energy can be conserved if the minimum power is used for transmission instead of the maximum. Secondly, the radio unit consumes a significant amount of energy. Up to 56% and 84% of energy are used by the radio if the sensor transmits at minimum and maximum power levels, respectively. The results are validated by the CC1000 data sheet which is the employed radio in Mica2. According to [CC1000], the required current consumption for -20 and +10 dBm are 6.9 and 26.7 milli-amp (mA), respectively. Therefore, over 74% can be conserved and this is close to the 75% which is obtained from PowerTOSSIM.

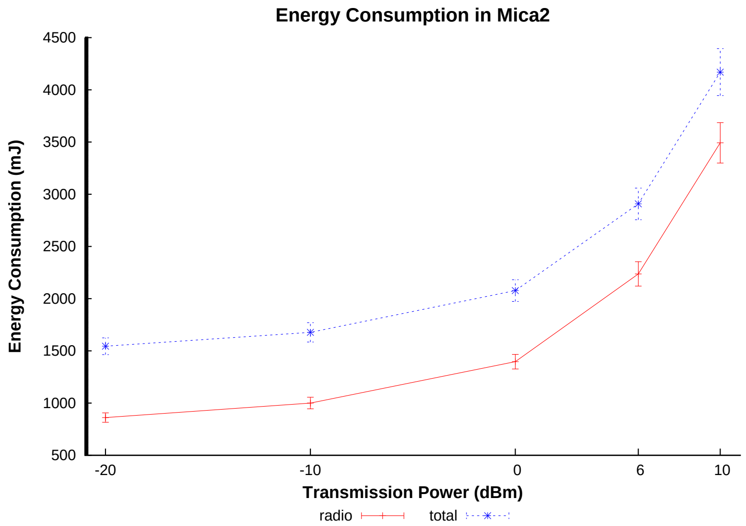


Figure 4.1: Radio and total energy consumption at various transmission power levels

Table 4.2: Average radio power consumption (mJ) and percentages of used and saved power

Transmission Power (dBm)	Average of Radio Power Consumption (mJ)	Percentage of Used Power	Percentage of Saved Power
-20	861.52	24.67	75.33
-10	1000.33	28.64	71.36
0	1396.44	39.98	60.02
+6	2236.90	64.05	35.95
+10	3492.48	100	0

Two key motivations are established with respect to the simulation results. Firstly, transmission power considerably affects radio power consumption. The power-aware approach based upon power adaptation is Transmission Power Control (TPC). PoRAP adopts the TPC concepts in order to achieve the power conservation goal. The selected sensor platform in this dissertation is Tmote and it employs the CC2420 radio instead of the CC1000. Like the CC1000, the CC2420 also supports transmission power adaptation but it provides a different range of power levels. Table 4.3 shows some of the possible power levels and the corresponding current consumption [CC2420]. An analysis of power conservation with respect to the maximum level is also shown.

Table 4.3: Transmission power levels provided by CC2420 and analysis of power conservation

Transmission Power (dBm)	Current Consumption (mA)	Percentage of Used Current	Percentage of Saved Current
-25	8.5	48.85	51.15
-15	9.9	56.90	43.10
-10	11.2	64.37	35.63
-7	12.5	71.84	28.16
-5	13.9	79.89	20.11
-3	15.2	87.36	12.64
-1	16.5	94.83	5.17
0	17.4	100	0

According to Table 4.3, over 50% of power can be saved if the minimum power is used for data transmission. The transmission power is one of the main factors which produces different reception strengths. The power adaptation is based upon the current link quality in order to maintain a good link. However, power adaptation is based upon several factors affecting link quality such as distance and time-of-day.

Secondly, according to Figure 4.1, the radio unit accounts for a significant amount of power compared to the total consumed by all hardware components. Keeping the radio in sleep mode after the sensor has transmitted the data may establish an enhancement in power conservation. This is feasible if the single-hop network sensors do not listen to transmissions from other nodes in order to discover optimal data paths. The schedule-based MAC (Medium Access Control) approach suits the direct communication scenario as each of the sources wake up for control reception and data transmission. Otherwise, they are in sleep mode and consume the least amount of communication energy.

4.3 Analyses of Attenuation Models

This section provides details of three main models which estimate received signal strength (P_r) given transmitted strength (P_t) and hardware factors such as antenna gains. Several drawbacks of applying the model based approach in order to predict the received strength are also discussed.

4.3.1 Existing models

Three proposed models including Free-Space Propagation, Two-Way Ground Reflection and Shadowing models are given in the following paragraphs.

A) Free-Space Propagation Model

The first reviewed model is free-space propagation. The radio signal is assumed to travel in a straight line in all directions. Another main assumption is that the working space is free from absorbing or reflecting radio energy caused by any objects [McLa97]. The $P_r(d)$ at a distance d from the transmitter is shown in Equation (4.1).

$$P_r(d) \quad = \quad P_t\, G_t\, G_r\, \lambda^2 \,/\, (4\pi)^2\, d^2\, L \tag{4.1}$$

The transmission power is indicated by P_t. The G_t and G_r are the transmitter and receiver antenna gains (dBi), respectively. The L is system loss factor which is equal or greater than 1 ($L \geq 1$). The λ is the wavelength (m). According to Equation (4.1), the power loss is proportional to the square of the distance.

B) Two-Ray Ground Reflection Model

Instead of only assuming straight line radio propagation, the two-ray ground reflection model also includes the propagation of ground reflected path effects by determining the heights of both transmitter and receiver antennas. The $P_r(d)$ can be calculated from Equation (4.2).

$$P_r(d) \quad = \quad P_t G_t G_r h_t^2 h_r^2 / d^4 L \qquad (4.2)$$

All P_t, G_t, G_r and L definitions are the same as described in the previous model. The h_t and h_r are the heights of transmitter and receiver antenna, respectively.

C) Shadowing Model

Shadowing is an improved probabilistic model whereas the previous two deterministic models only determine the received signal strength in the context of transmitter-receiver (T-R) separation distance. The free-space propagation model represents an influence region of the transmitter as an ideal circle. The number of radio propagation paths is not limited to two as assumed in the two-ray ground reflection model. The shadowing model defines the signal strength at the distance d away from the transmitter as a sum of the path loss model value and a Gaussian random variable. The path loss model predicts the mean received power at a distance d using a close-in distance d_0 as a reference. If the $P_r(d)$ is a mean received signal power at the distance d, and $P_r(d_0)$ is that of d_0 then:

$$P_r(d) / P_r(d_0) \; = \; (d / d_0)^{\beta} \qquad (4.3)$$

where the β is the path loss exponent. It is empirically determined by field experiments. It is suggested its value to be 2 for an open area, and 2.7 to 5 for an urban area. The Gaussian random variable (X_{db}) describes the variation of signal received power at a certain distance. The received power regarding this model is shown in Equation (4.4).

$$[P_r(d) / P_r(d_0)]_{db} \; = \; -10\, \beta \log(d / d_0) + X_{db} \qquad (4.4)$$

4.3.2 Analysis

The models described earlier are proposed in order to estimate received signal power (P_r). According to Equations (4.1) to (4.4), the distance between the transmitter and receiver is a significantly important factor. In the case of the free-space model, the P_r is conversely related to the square of distance (d^2) as the propagating signal is assumed as an ideal circle. The effects of antenna heights are included in the two-ray ground reflection model. The received strength proportionally increases with the square of antenna heights. Further, the distance greatly affects the strength in the two-ray model. Similarly, the distance is crucial in the shadowing model. In conclusion, the location of sensors is important in determining the transmission strength in order to meet a desired received strength.

Apart from the sensor locations, there are several variables for estimating the received strength. These variables maybe grouped into two categories. The first is hardware dependent such as antenna gains and heights. The second relates to operating factors such as system loss factor and wavelength. These variables are hard to determine. Even if the same sensor platform is deployed, the effects of hardware difference cannot be neglected. Each sensor therefore requires some memory for variable information. Furthermore, additional calculations for received strength estimation are required.

The proposed models do not capture all the factors that affect the signal strength in the field such as absorption and blocking. Thus, they are not good predictors of the actual receiving strength or attenuation. PoRAP employs a measurement-based scheme for collecting the real-time link quality metrics reflecting the received signal strength and it uses this data to discover an optimal power setting for each link. The next section addresses factors which significantly affect the received signal strength. The inadequacy of model-based prediction will be also addressed by using some of the experimental results.

4.4 Experimental Investigation of Transmission Power and Reliability

This section provides details of experimental studies aimed at establishing effects of transmission power, distances and time-of-day on link quality metrics. In total three metrics including RSSI (Received Signal Strength Indicator), LQI (Link Quality Indication) and PRR (Packet Reception Rate) are used to describe the effects. The relationships between the metrics are also investigated and will be used for establishing power adaptation policies.

4.4.1 Link quality metrics

There is a variety of sources which cause variability in link quality in wireless communication. Unlike wired communication, environmental factors such as climatic conditions and time-of-day also affect the degree of signal attenuation. A significant degree of signal attenuation or interference may lead to unsuccessful data transmission. Link quality measurement is therefore one of the major issues in wireless network communication.

A transmitter sends data packets at a specific transmission power wirelessly over a medium to a receiver. The transmission power level is programmable and this capability is provided by a transceiver or radio unit which is a component responsible for data transmission and reception. A sensor communicates with the other node by sending and receiving messages via wireless channel which is normally air. Several signals are generated from various sources such as electronic appliances and they are dissipated to the air. A wireless channel may then have background noise which is capable of interfering with data delivery between a pair of nodes. Moreover, time-of-day and climatic conditions such as fog and rain affects the wireless link quality. In order to determine link quality characteristics, all causes of signal strength reduction are considered as sources of signal attenuation. The reduced magnitude in signal strength is therefore defined as signal attenuation. If the transmission power is less than signal attenuation, the message cannot be successfully received. When the receiver is not able to receive the sent packet and the number of received packets is not increased, the reliability requirement defined by an application may not be met. Transmission power should be adjusted in response to the changing link quality.

A radio unit provides several mechanisms to measure received signal power. The measured values are categorised as received signal strength (RSS). In total two attributes including RSSI (Received Signal Strength Indicator) and LQI (Link Quality Indication) are in the RSS category. The RSS can be used to indicate link quality. The reliability requirement specified by an application indicates a required number of packets received at the base station. The percentage of data receptions can be used to describe the link quality. The packet reception rate (PRR) is therefore introduced. Relationships amongst transmission power (TX), received signal strength (RSS) based attributes and PRR is useful for mapping application requirements to link quality measurements. Thus, the transmission power is adapted in order to provide reliability of packet reception.

A) Received signal strength indicator

Received Signal Strength Indicator (RSSI) is defined as a measurement of the signal strength of an incoming message. The transmitted signal strength or transmission power reduces as the signal propagates through the medium. The RSSI is measured at the receiver and it demonstrates the received signal strength. Therefore, signal attenuation is approximately the difference between the transmission power and the RSSI.

According to [CC2420], the mechanisms required to measure the RSSI is built-in and can be read from the 8-bit, signed 2's complement register, `RSSI_VAL`. Therefore, there are possible 256 values of RSSI register value. Another register, `RSSI_VALID` is used to conduct RSSI measurement by being enabled for at least 8 symbol periods which are equal to 128 microseconds. The RSSI register values are averaged over the measuring interval and the average is then converted to the power P by applying Equation (4.5).

$$P = RSSI\_VAL + RSSI\_OFFSET \tag{4.5}$$

where the $RSSI\_OFFSET$ is found empirically during system development and is approximately equal to -45 dBm. The above equation and approximated values are stated in [CC2420]. The power P, indicating measured RSSI value has a unit of dBm. From this point onwards in this thesis, the RSSI refers to the P obtained from Equation (4.5).

Two categories of transceiver can be made. The first category is based upon the lower operating frequency, which is less than 1,000 Megahertz (MHz). The transceiver in this group is numbered 1000 such as CC1000 and TR1000 [RFM]. The second category operates at around 2,400 MHz and is numbered 2420. CC2420 and EM2420 [EM2420] are in this category. Both categories implement RSSI measuring mechanisms. Therefore, using RSSI as a metric for link quality measurement is feasible for most of the transceivers in the market. Apart from the RSSI, the 2420 numbered transceiver propose LQI (Link Quality Indication) as an additional metric. Several details of the LQI are given in the following paragraphs.

B) Link quality indication

Link Quality Indication (LQI) is another metric in the RSS-based category. According to the definition outlined in IEEE 802.15.4 Standard for Local and Metropolitan Area Networks, the LQI measurement is a characterisation of the strength and/or quality of received packet. Each received packet has its own LQI measurement and the integer value ranges from 0 to 255. Therefore, the minimum and maximum values of LQI for each packet are 0 and 255, respectively. The IEEE standard recommends at least eight unique values of LQI should be used in order to yield a uniform distribution between the two limits. The following details of LQI are based upon the CC2420 radio unit as it is used in both Tmote Sky and Tmote Invent which are the chosen platforms in this research.

There are several LQI computational schemes stated in [CC2420]. Firstly, LQI can be estimated from the RSSI value by using MAC (Medium Access Control) software which is responsible for generating an appropriate scaling of the LQI for a given application. The LQI can be therefore determined as a redundant RSSI. A major drawback of the RSSI-based estimate approach is observed. The computed LQI may be increased by a narrowband interferer inside the channel bandwidth. The increased LQI means a better link quality but in reality, the link performance is reduced as a result of interference. The CC2420 transceiver provides another approach to calculate the LQI of incoming packet.

An average correlation value of each incoming packet is provided by the transceiver. The value is based on the first 8 symbols or bits following the SFD (Start of Frame Delimiter). The unsigned of 7-bit value can be determined as a "chip error rate". Note that the CC2420 does not provide chip decision mechanisms. After the average has been computed, it is appended to each received frame together with the RSSI and CRC (Cyclic Redundancy Check) OK/not OK. A consideration of CRC is enabling by setting the `MDMCTRL0.AUTOCRC`. The CRC is a function used to detect any accidental alteration of data during transmission. A data stream of any length is input to the CRC function and it produces a value of a certain fixed size as an output. A correlation value of around 50 and 110 associated with the minimum and maximum limits indicates the lowest and highest quality frames detectable by the CC2420. A correlation value can be converted to the LQI by using Equation (4.6).

$$LQI = (\,CORR - a\,)\, b \tag{4.6}$$

An obtained LQI output is limited to the range of 0 through 255. Both a and b are found empirically based on PER (Packet Error Rate) measurements as a function of the correlation value. The LQI may be obtained from a combination of RSSI and correlation values. However, TinyOS treats LQI differently. The LQI is perceived as the measurement of how close the observed bits were to their values. Therefore, the LQI measurements from TinyOS may be related to the bit error rate.

C) Packet reception rate

Apart from RSSI and LQI, PoRAP determines an additional link quality index. The main reason is that both RSSI and LQI are not transparent to the user or application. Mapping mechanisms are required in order to convert an application requirement to the ranges of RSSI and LQI values the base station should have. This subsection aims to describe the Packet Reception Rate (PRR) which is more closely related to the application requirement.

Wireless sensor networks are application specific and each application defines its own required number of received packets collected by the base station as shown in Equation (4.7).

$$\textit{Reliability Requirement } (\%) = P\ (packets) \pm \varepsilon \tag{4.7}$$

In this research, the PRR is defined as a percentage of the number of correctly received to that of transmitted packets as shown in Equation (4.8). The PRR value is in the range of 0% to 100%. The 100% PRR indicates complete reliability.

$$PRR\ (\%) = (\textit{No. of correctly received packets / No. of sent packets}) \times 100 \tag{4.8}$$

Each received packet has its own measured RSSI and LQI which can be used to predict the PRR. Models representing relationships amongst metrics are therefore required and demonstrated later in this chapter.

4.4.2 Experimental setup

In our implementation-based experiments, Tmote Invent and Tmote Sky are used as the sensor and base station, respectively. Both of them employ the CC2420 radio which has working frequency band from 2,400 to 2,483 Megahertz (MHz). The radio transmission data rate is 250 kilobits per second (kbps). The random access memory (RAM) and program flash sizes are 10 and 48 kilobytes (Kbytes). The main difference between both platforms is that the Tmote Invent provides built-in sensor and battery boards. The minimum and maximum transmission power levels are -25 and 0 dBm, respectively. Tmote sensors consume 8.5 and 17.4 milli-amps (mA) for transmitting a data packet at minimum and maximum power levels, respectively. A current of 19.7 mA is required for radio receiving. This indicates that receiving accounts for a large radio power usage. Listening removal in PoRAP may enhance power conservation in WSNs. Each Tmote sensor includes an internal Inverted-F antenna which is a wire monopole. The top section of the antenna is folded down to be parallel with the ground plane. The communication ranges for indoor and outdoor are 50m and 125m, respectively.

A sensor can be considered as a tiny computing device. It is capable of sensing several physical data elements as well as communicating with the other nodes. The sensor has limited resources and therefore requires a specifically developed operating system (OS). Amongst several proposed operating systems for WSN, TinyOS is widely used in both academic and industrial industries. TinyOS is a free, open-source component based operating system specifically developed for WSN. It is written in the nesC programming language which is a dialect of the C language. The TinyOS project was started by the University of California at Berkeley in cooperation with Intel Research. A developer is able to write TinyOS application and install it on sensors. TinyOS applications are component based as they consist of several components which communicate via provided and used interfaces. A component must implement an interface it provides or uses. The wiring details between each pair of components are stated in the configuration file.

The selected release of TinyOS for sensors and base station in this research is TinyOS 2.0.2 where a new standard message buffer called `message_t` is introduced. The `message_t` consists of header, footer, and metadata structures corresponding to the link layers. For example, the CC2420 radio implementation defines its structures (`cc2420_header`, `cc2420footer` and `cc2420_metadata`) in `CC2420Msg.h`. Each structure consists of several field definitions. For example, `rssi` and `lqi` are defined in the `CC2420_metadata`. The `message_t` does not allow the components to directly access any of its field. The component which introduces new packet fields should provide an interface to the fields for an access by other components.

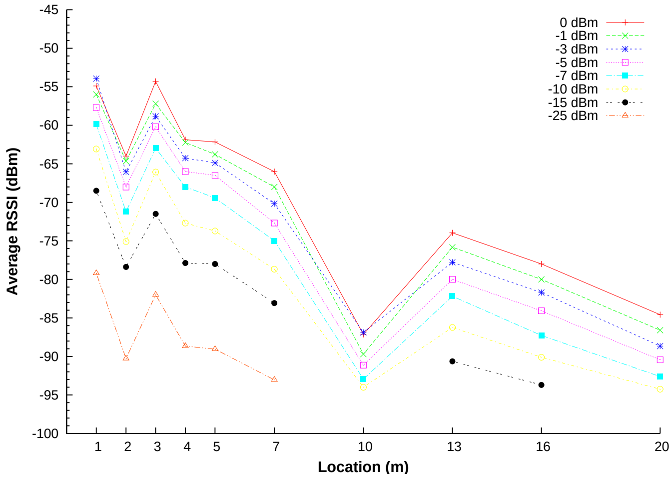
In TinyOS 1.x, the components access the required fields via the offsets of standard message structure such as `TOS_Msg.strength` for the RSSI or `TOS_Msg.lqi` for the LQI. However, both RSSI and LQI values can be obtained by calling `CC2420Packet.getRssi(msg)` and `CC2420Packet.getLqi(msg)`. The `CC2420Packet` is an interface provided by the `CC2420ActiveMessageC` component and the `msg` is the received message. Regarding the CRC, the CC2420 metadata structure has the `crc` field which is of Boolean type. In conclusion, TinyOS 2.x supports both transmission power adaptation and link quality measurements capabilities in PoRAP.

The experiments were conducted in the 16m x 20m indoor environment. The base station was plugged into a desktop computer and received data from sensors. Three sensors were used and they were placed at the same locations. In total 10 locations including 1, 2, 3, 4, 5, 7, 10, 13, 16 and 20m were used. The sensors and base station had the same antenna orientation and height above floor level. The payload size was 12 bytes. In total 8 transmission power levels including 3, 7, 11, 15, 19, 23, 27 and 31 associated to -25, -15, -10, -7, -5, -3, -1 and 0 dBm were used. The sensors transmitted one packet every second. At each power, the sensors transmitted 50 packets for statistical analysis. Upon data reception, the base station measured RSSI and LQI. The number of received packets was counted in order to compute PRR.

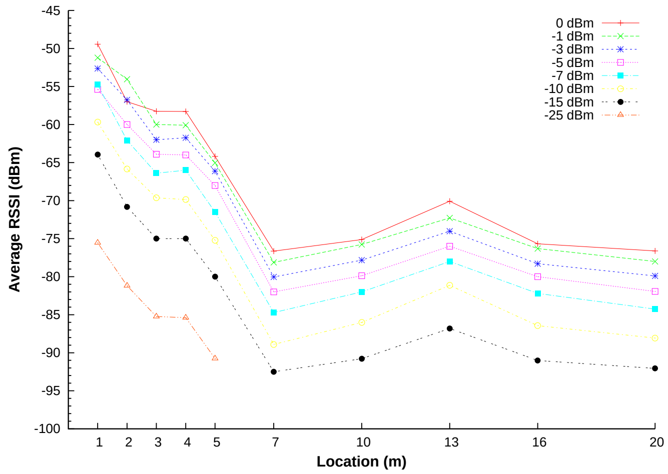
4.4.3 Experiments on location as a determination of necessary transmission power

The significance of the locations of the sending and receiving motes to determine the relationship between transmission power (TX) and reception quality is established. In this experiment, the base station location was the same whilst three sensors were placed at 10 different locations in the same direction with clear line-of-sight (LOS) including 1, 2, 3, 4, 5, 7, 10, 13, 16 and 20m. Each power adaptation cycle was ended after the maximum power had been reached. The other experimental parameters such as power levels, data sending rate and number of runs are stated in Section 4.4.1.

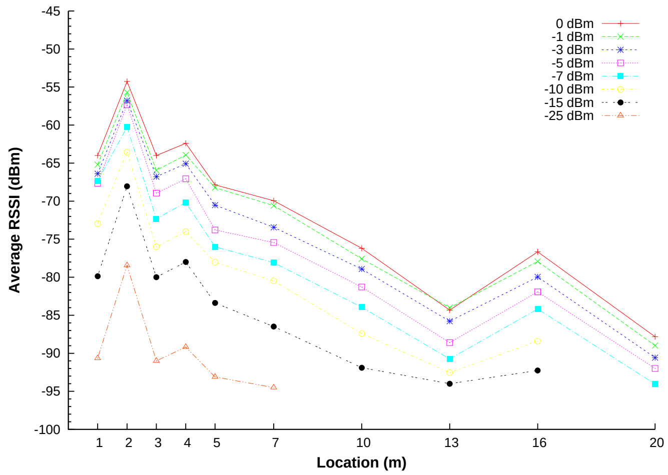
Figure 4.2 shows the average RSSI readings of the three sensors at various locations and transmission power levels. The missing data indicate that the power provides RSSI reading less than -95 dBm which is the minimum value reported by TinyOS. Figure 4.3 shows average LQI readings of the three sensors at various locations and transmission power levels. The missing data indicate unsuccessful data delivery.



(a) Sensor 1

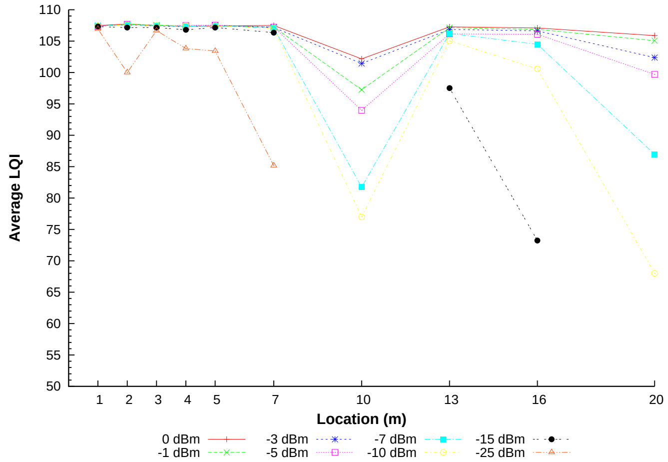


(b) Sensor 2

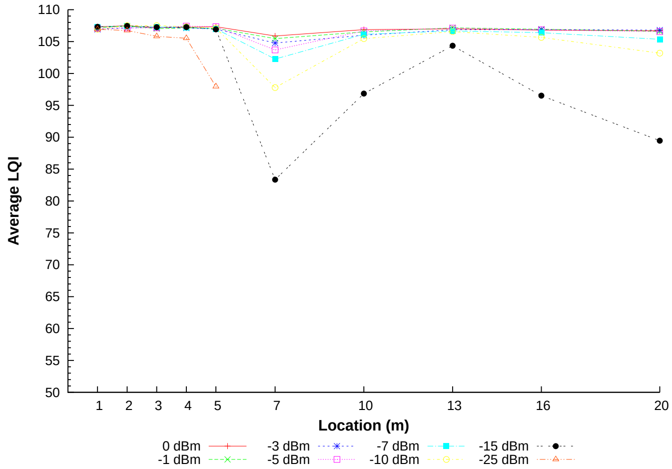


(c) Sensor 3

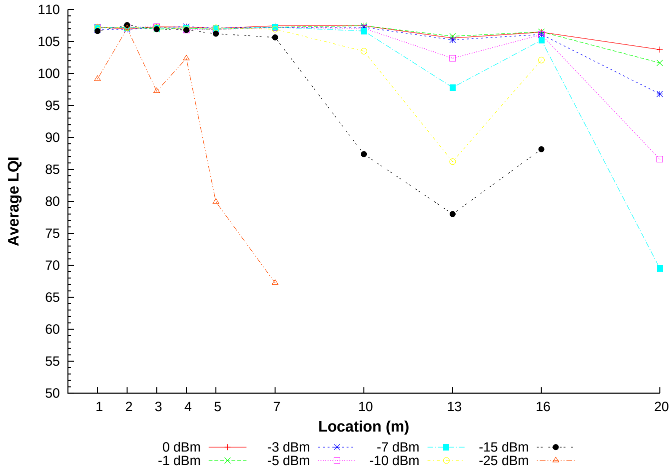
Figure 4.2: Effects of sensor locations on RSSI



(a) Sensor 1



(b) Sensor 2



(c) Sensor 3

Figure 4.3: Effects of sensor locations on LQI

According to Figure 4.2 and Figure 4.3, several observations can be made as follows:

1. Most of the RSSI measurements proportionally increased with the transmission power levels. Unlike the RSSI, the LQI measurements were stable at closer locations especially when higher power was used for transmission. Most of the LQI values decreased at greater distances.

2. The minimum power level of -25 dBm could be used by all sensors to successfully deliver data to the base station only when the locations were within 5m. A location distance of 7m was achieved by Sensors 1 and 3.

3. At each transmission power level, different RSSI and LQI readings were obtained when the sensors were placed at different locations. A significant variation in the average of RSSI measurements is observed from different sensor locations. The decrease in received signal strength with increasing distances assumed in the prediction models do not apply in our results. For example, in the case of Sensor 1, 2m provides a weaker strength compared to a distance of 3m. Similar observation applies to Sensor 2 at 7m and Sensor 3 at 1m. The experimental results given in [LZZ+06] and [SKPP07] demonstrate similar observations on location effects.

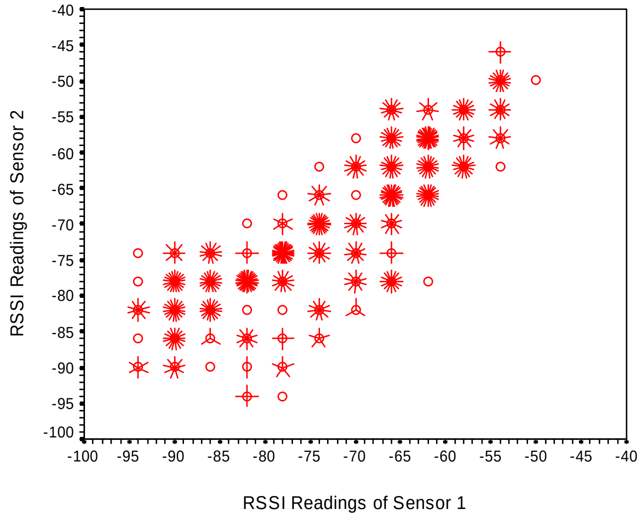
4. The RSSI and LQI are measured only when the base station receives data. The observed minimum RSSI values higher than -95 dBm indicate data reception.

4.4.4 Variation in link quality metrics as a result of different sensors

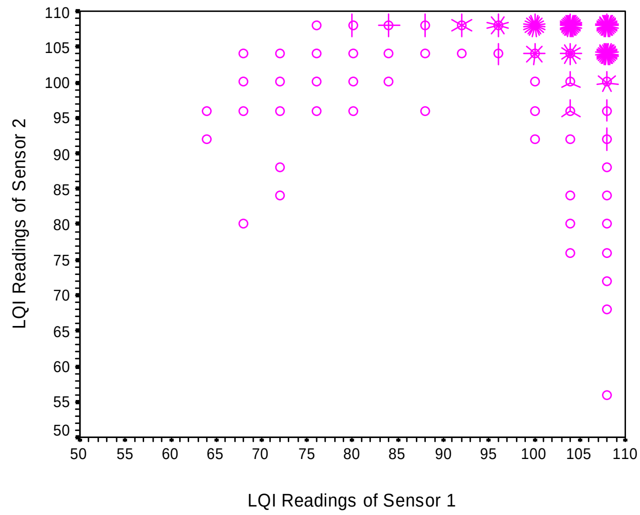
We have found from the previous section that transmission power and sensor location are two key factors which affect the received signal quality. Applying the model-based approach may not sufficiently provide an accurate estimation. In this section, variations in link quality metrics as a result of different sensors are addressed.

Raw RSSI and LQI readings at all power and locations are plotted against those values of Sensor 1 which is defined as the reference sensor. Figure 4.4(a) and (b) show sunflower plots of raw RSSI and LQI readings of Sensor 2 compared to Sensor 1, respectively. The sunflower plot represents the density of the observed data. Each petal represents 5 readings or cases.

A linear correlation between RSSI readings of Sensor 1 and 2 is observed in Figure 4.4(a). Most of the output is located near the diagonal region. Furthermore, most of the sunflowers comprising of many petals are higher than the diagonal line which indicates similarity in the output. This implies that Sensor 2 provides higher RSSI than Sensor 1. Both sensors provide most of the LQI values between 100 and 110. This observation confirms the LQI plots in Figure 4.3 where the output mostly lies within the same range.



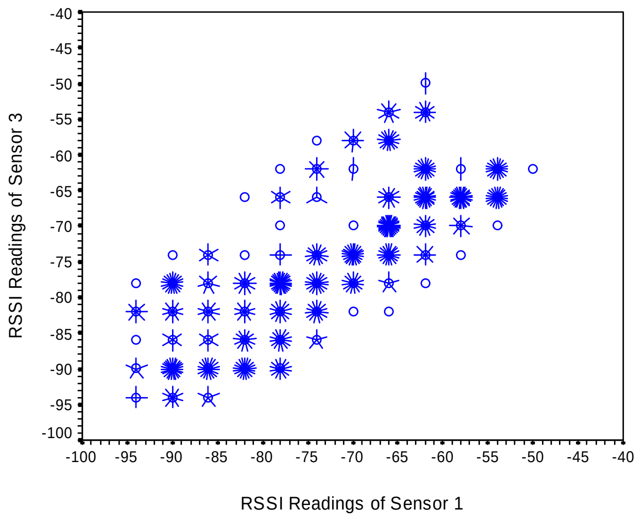
(a) RSSI



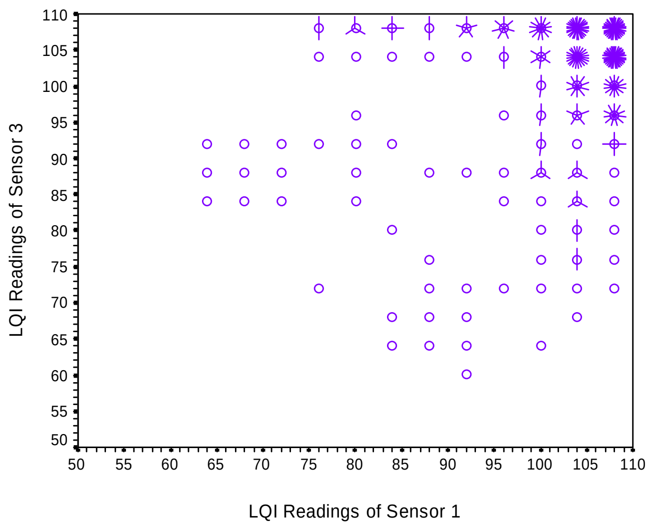
(b) LQI

Figure 4.4: Sunflower plots of Sensor 2 compared to Sensor 1

Figure 4.5(a) and (b) show sunflower plots of raw RSSI and LQI readings of Sensor 3 compared to Sensor 1, respectively. Similarly, each petal represents 5 readings or cases. Like the previous RSSI plot, strong correlation between RSSI measurements of Sensor 1 and Sensor 3 is observed. However, Most of the output density lies below the diagonal line. Unlike Sensor 2 which provides higher RSSI, lower output is produced by Sensor 3. The same observation on LQI applies to Sensor 3.



(a) RSSI



(b) LQI

Figure 4.5: Sunflower plots of Sensor 3 compared to Sensor 1

In Summary, different sensors result in different link quality metrics. This is mainly because each sensor is comprised of several hardware components such as ADC (Analogue-to-Digital Converter) and transceiver. The manufacturing processes results in different output or performance. Both RSSI and LQI should be monitored at the base station for two main reasons. Firstly, the metrics significantly vary with a number of several factors such as transmission power, location and deployed environment. Secondly, different sensors provide different link quality metrics. PoRAP therefore adapts transmission power on a per-sensor basis.

4.4.5 Fluctuation in link quality metrics over time of day

This section investigates on how RSSI, LQI and PRR fluctuate over the time of day. The same base station and Sensor 1 were used. The sensor was located at 20m in the same environment. It transmitted one packet every second at 0 dBm for 1,440 minutes or 24 hours. The experiment was started in the morning before the office hour.

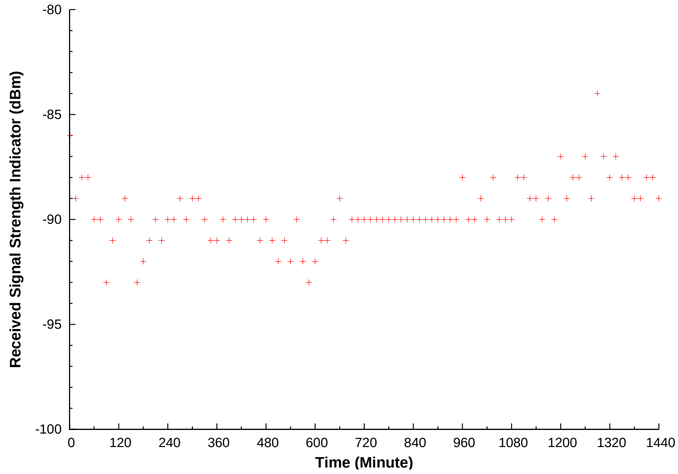
Figure 4.6 demonstrates fluctuation of the RSSI, LQI and PRR over time of day. The RSSI fluctuated during the first half of the experiment. It was stable during the night time and the fluctuation was back later in the experiment. Unlike the RSSI, the LQI fluctuated throughout the experiment. At the beginning the PRR siginificantly decreased. This observation was resulted from the presence of people around the lab. The PRR increased during the night time as there were no staff and student in the lab.

In summary, apart from transmission power, location and heterogeneity in the manufacture, the link quality metrics are affected by the time-of-day. The presence of people around the lab is the main factor in this experiment and is considered as temporary physical barrier. Radio communication in WSNs requires a line-of-sight. Some packets may be lost if there are some people in the sending path.

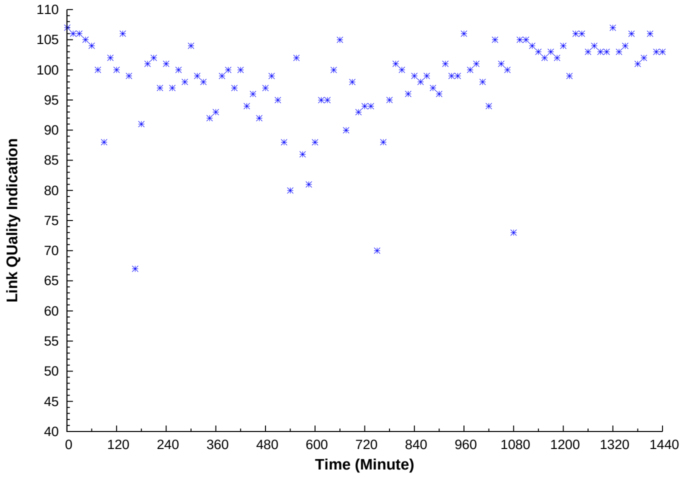
4.4.6 Relationship between metrics

This section aims to describe the relationships between RSSI, LQI and PRR. During packet reception, the base station measures RSSI and LQI. Apart from RSSI and LQI, the standard message type of TinyOS includes the CRC field which is a Boolean data type. The base station also looks at the CRC field to see if the data packet is received correctly. The numbers of data transmissions and receptions are counted to compute the PRR. This scheme can be used in a long-term operation.

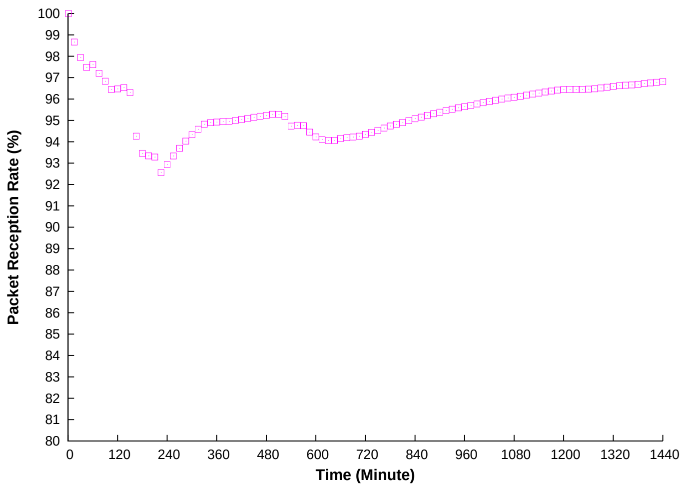
However, the PRR may be estimated from the RSSI or LQI measurements. This concept suits a short term operation. The base station does not count the numbers of sent and received packets. Hence, the relationship between metrics needs to be established. Figure 4.7 shows relationships between the link quality metrics at 5m, 12m and 19m. The average RSSI and LQI are computed at each transmission power level. The number of received packets is counted in order to calculate the PRR.



(a) RSSI

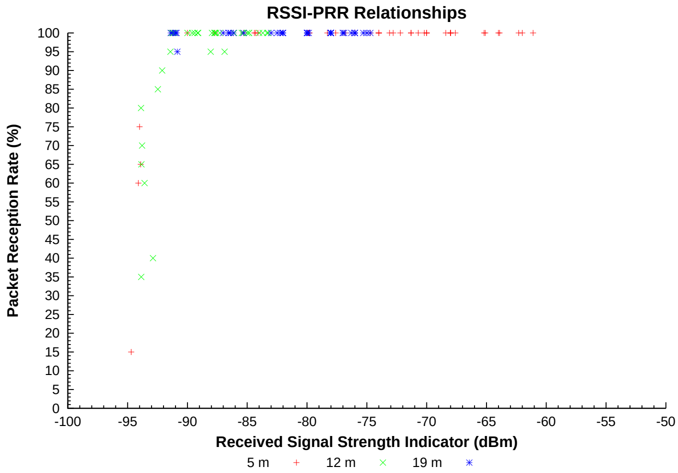


(b) LQI

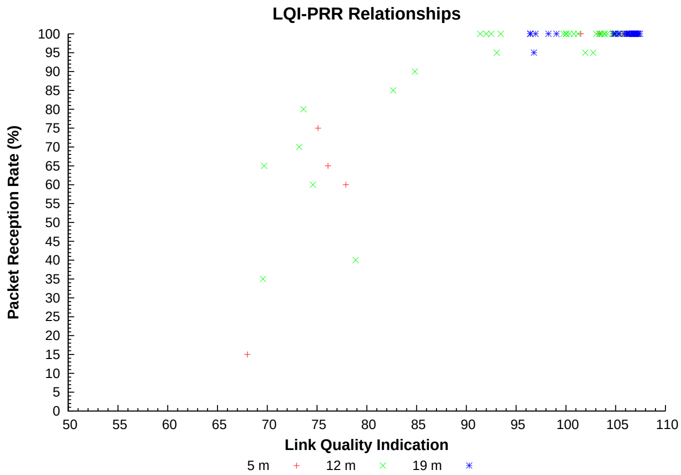


(c) PRR

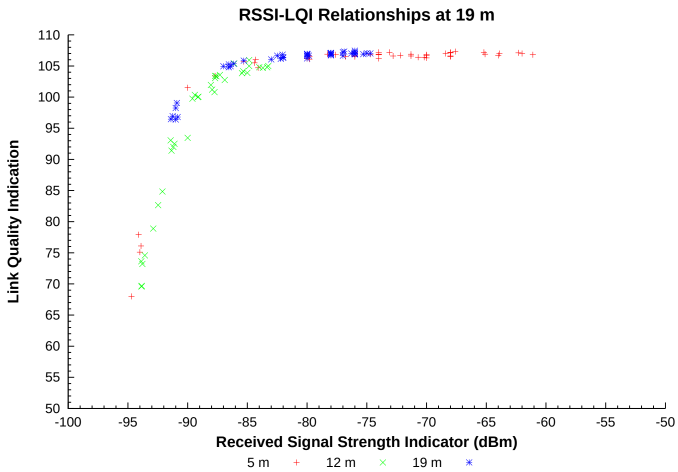
Figure 4.6: Fluctuation in link quality metrics over 24 hours



(a) RSSI-PRR



(b) LQI-PRR



(c) RSSI-LQI

Figure 4.7: Relationships between metrics

According to Figure 4.7, several observations can be made as follows:

1. The PRR steeply increases with RSSI up to a certain point followed by more stable reliability measurements. Significant variations in reception rates are found when the RSSI readings are between -95 and -90 dBm. At least 95% PRR may be achieved at all distances if the sensor transmits data at the power producing RSSI greater than -90 dBm.

2. The higher LQI results in a more stable PRR. The relationship between LQI and PRR shown in Figure 4.7 (b) is less clear than Figure 4.7 (a). Similar results are also addressed in [LZZ+06]. According to these observations, RSSI should be used to relate to the PRR.

3. The LQI significantly increases with the RSSI. Convergence to particular LQI values is then observed. A lower bit error rate is observed when the base station receives packets with higher RSSI measurements.

The relationship between link quality metrics can be used to estimate an observed reliability from the measured receiving strength. This observation is addressed in [LZZ+06] and [SDTL06]. After measuring the metrics, the base station determines whether the current transmission power requires an adaptation. The PRR steeply increases with the RSSI followed by significantly more stable measurements. The PRR should not be estimated from the RSSI between -95 to -90 dBm as transmission power adaptation based upon this region will not be accurate. The measurements demonstrate that the network should operate at levels taken from an appropriate region.

In summary, the measurements demonstrate the necessities of link quality measurement as both RSSI and LQI vary with transmission power, distance, location, heterogeneity in hardware manufacture and time-of-day. The relationship between signal strength and distance confirms that the existing models do not capture all factors. The PRR should be also used as it directly relates to reliability. The relationship between RSSI, LQI and PRR is addressed and it is confirmed by the previous studies such as [LZZ+06] and [SDTL06]. The RSSI relates to the PRR more clearly than the LQI. The network should operate in the region where the RSSI produces a stable PRR. As link quality is affected by several environmental factors and interference, the transmission power adaptation should be conducted in order to minimise data loss. In this dissertation, the minimum and maximum RSSI is defined by looking at the RSSI-PRR relationship obtained from the same operating field. The base station measures the RSSI and compares it to the thresholds. Transmission adaptation will then follow by notification to each of the sources.

4.5 Delays in Wireless Sensor Networks

This section provides some experimental results on delays in wireless sensor networks (WSNs) which affects PoRAP architecture development. Communication is represented by a frame structure which consists of several slots. A slot is assigned to each source and it transmits data when the allocated slot arrives. The slot length should be long enough to avoid data collisions at the base station where two packets from two different sources arrive approximately at the same time. Several experiments have been conducted in order to investigate some factors which affect the delays, including heterogeneity in sensor manufacturing and payload sizes.

4.5.1 Timestamp measurements and delay calculations

Details of timestamping scenario and delay calculations are given. As the base station does not know when the source is booted, at the beginning it broadcasts the control packet periodically. The periodic broadcast was set to 1 second. After the source is booted, it starts its transmission after the packet has been received. Similarly, the base station starts the next transmission after it has received the packet back from the source. Packet timestamping mechanisms and delay calculations are respectively illustrated in Figure 4.8 and Table 4.4.

According to Figure 4.8, the base station is booted at x_0. When the base station is ready to send, the timer is set to be fired at x_1 and `send` command is called at x_2. A timer is used in order to trigger packet transmission. Prior to transmission, the base station sets some fields in the message structure such as its id and transmission power. The SFD (Start of Frame Delimiter) transmission occurs at x_3. The timestamp is created and the packet payload content is modified to include the time of the transmission. Therefore, the fire-to-send and send command delays of the base station are equal to $x_2 - x_1$ and $x_3 - x_2$. The packet is completely transmitted by the radio at x_4 and the transmission delay is $x_4 - x_3$.

After being booted at y_0, the source receives the SFD at y_1. The receive event of the radio and application are signalled at y_2 and y_3 when the source receives the packet. The reception and receive delays of the base station are therefore y_2 - y_1 and $y_3 - y_2$. Once the packet has been received, the source requires some duration to process the information obtained from the packet. It then sets up its own transmission and the bits of packet are loaded into the radio buffer. The timer is fired at y_4 and the `send` command is called at y_5. The SFD is transmitted at y_6. Hence, the send command delay of the source is equal to $y_6 - y_5$. The transmission delay is $y_7 - y_6$. Table 4.4 summarises the delay calculations.

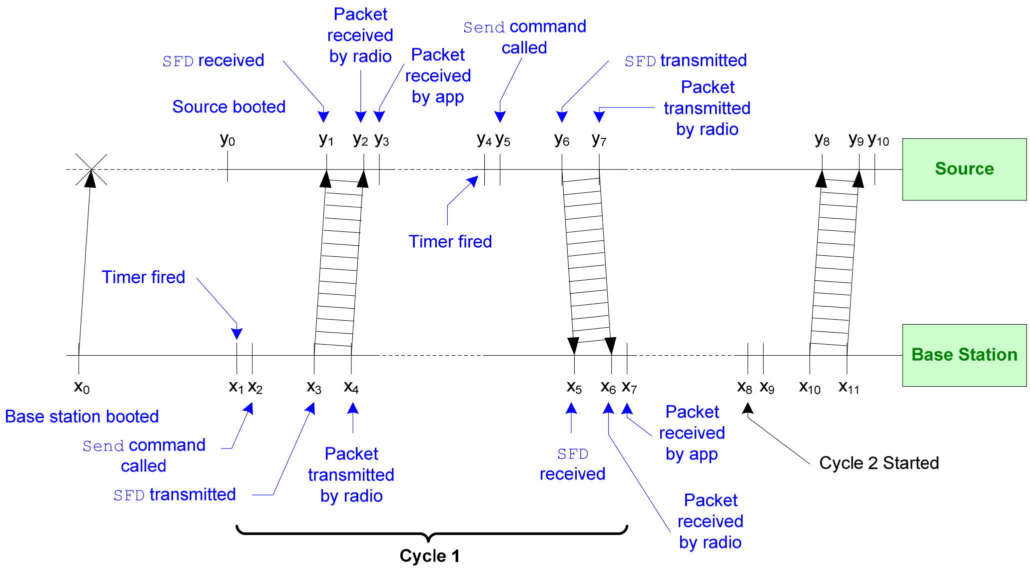


Figure 4.8: Timestamp at various events

Table 4.4: Summary of delay calculations

Delays	Calculations
Base Station	
▪ Fire-to-Send	$x_2 - x_1$
▪ Send Command Delay	$x_3 - x_2$
▪ Transmission	$x_4 - x_3$
▪ Reception	$x_6 - x_5$
▪ Receive	$x_7 - x_6$
Source	
▪ Reception	$y_2 - y_1$
▪ Receive	$y_3 - y_2$
▪ Fire-to-Send	$y_5 - y_4$
▪ Send Command Delay	$y_6 - y_5$
▪ Transmission	$y_7 - y_6$
Two-Way Propagation	$(x_5 - x_3)$ - $(y_6 - y_1)$

According to Table 4.4, the transmission and reception delays are calculated based upon when the events take place. The transmission delay is defined as the duration required for the radio to transmit the packet. In TinyOS 2.x, the `CC2420Transmit` interface provides a `sendDone()` event which notifies packet transmission completion. The reception delay is the duration required for packet reception by the radio, and the `receive` event is used for the timestamp. The fire-to-send delay indicates the desired interval for starting packet transmission after the timer is fired.

One Tmote Sky base station and one Tmote Invent source were used. The source was located at 0.5 m away from the base station. The base station was plugged into a desktop computer. In total 1,000 cycles of message exchange were run for each source. After the packet had been received, the node waited for 128ms and initiates its data transmission.

4.5.2 Experimental results

Two factors affecting WSNs delay are studied and the results are given. In total five different payload sizes and five different sources were used in this study.

A) Effects of payload size

In order to consider the effects of payload size, an additional experiment was conducted. The scenario shown in Figure 4.8 was used. All settings are the same except the payload sizes. In total five payload sizes were used including 39, 55, 75, 95 and 115 bytes. Note that the maximum payload for the CC2420 radio is limited to 117 bytes whilst the header size is 11 bytes. Send command and transmission delays of the source were determined. Two-way propagation delays were also computed. In the case of 39 bytes, reception and receive delays of source and base station were observed whilst all delays were observed for the larger payload sizes.

Send command and transmission delays

Statistical analysis of fire-to-send, send and transmission delays in milliseconds are shown in Table 4.5, 4.6 and 4.7, respectively.

The tables show that all delays increase with increasing payload sizes. The source requires more time to deliver larger packets to the radio. Similarly, larger packets require a longer duration for transmission. The relationships between the 50th percentiles or medians of all sending delays and payload sizes are shown in Figure 4.9. Note that "Send Command" delay is represented as "Send" in the figure.

Table 4.5: Statistical analysis of fire-to-send delays observed at source

Attribute		Payload Size (bytes)				
		39	55	75	95	115
Min		Not measured	0.50	0.59	0.72	0.81
Max			0.66	0.78	0.88	1.00
Percentiles	25		0.50	0.59	0.72	0.81
	50		0.50	0.59	0.72	0.81
	75		0.50	0.59	0.72	0.81
	90		0.50	0.59	0.72	0.81
	99		0.50	0.59	0.72	0.81
Cycles		999	1,000	1,000	1,000	999

Table 4.6: Statistical analysis of send command delays observed at source

Attribute		Payload Size (bytes)				
		39	55	75	95	115
Min		3.31	4.00	5.00	5.72	6.56
Max		13.00	13.69	14.69	15.41	17.22
Percentiles	25	5.69	6.38	7.60	8.09	8.94
	50	8.03	8.71	9.84	10.44	11.28
	75	10.53	11.22	12.31	12.96	13.78
	90	12.00	12.69	13.75	14.44	15.28
	99	12.91	13.59	14.59	15.34	16.16
Cycles		999	1,000	1,000	1,000	999

Table 4.7: Statistical analysis of transmission delays observed at source

Attribute		Payload Size (bytes)				
		39	55	75	95	115
Min		1.81	2.34	3.00	3.66	4.31
Max		1.84	2.34	3.00	3.69	4.31
Percentiles	25	1.84	2.34	3.00	3.66	4.31
	50	1.84	2.34	3.00	3.66	4.31
	75	1.84	2.34	3.00	3.66	4.31
	90	1.84	2.34	3.00	3.66	4.31
	99	1.84	2.34	3.00	3.69	4.31
Cycles		999	1,000	1,000	1,000	999

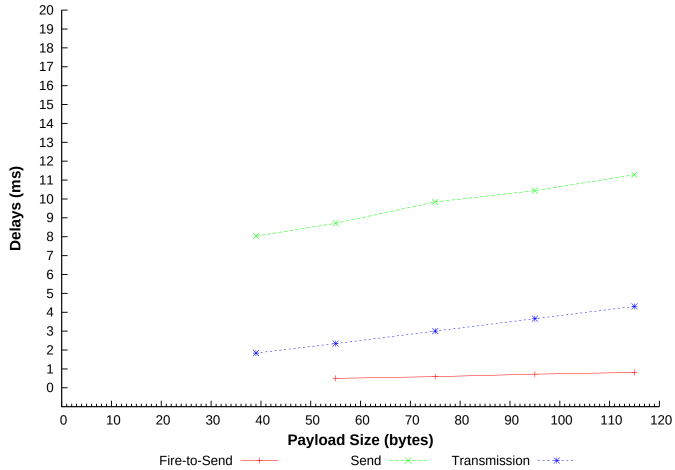


Figure 4.9: Relationships between source sending delays and payload sizes

Linear relationships between each delay and payload size are observed in Figure 4.9. Increases in send command and transmission delays are greater than those of fire-to-send delay.

Reception and receive delays

Statistical analyses of reception and receive delays in milliseconds are shown in Table 4.8 and Table 4.9, respectively.

Table 4.8: Statistical analysis of reception delays observed at source

Attribute		Payload Size (bytes)				
		39	55	75	95	115
Min		4.38	5.63	7.09	8.66	10.13
Max		4.47	5.66	7.16	8.96	10.19
Percentiles	25	4.41	5.63	7.13	8.66	10.16
	50	4.41	5.63	7.13	8.66	10.16
	75	4.41	5.66	7.13	8.69	10.16
	90	4.44	5.66	7.13	8.69	10.16
	99	4.47	5.66	7.16	8.69	10.19
Cycles		999	1,000	1,000	1,000	999

Table 4.9: Statistical analysis of receive delays observed at source

Attribute		Payload Size (bytes)				
		39	55	75	95	115
Min		0.19	0.19	0.19	0.19	0.19
Max		0.22	0.22	0.22	0.22	0.22
Percentiles	25	0.19	0.19	0.19	0.19	0.19
	50	0.19	0.19	0.19	0.19	0.19
	75	0.22	0.22	0.22	0.22	0.22
	90	0.22	0.22	0.22	0.22	0.22
	99	0.22	0.22	0.22	0.22	0.22
Cycles		999	1,000	1,000	1,000	999

According to Table 4.8, reception delays increase with increasing payload sizes. The radio unit inside the source requires more time to receive larger packets. However, the receive delays remain constant for all payload sizes. The relationships between the 50th percentiles or medians of both receiving delays and payload sizes are shown in Figure 4.10.

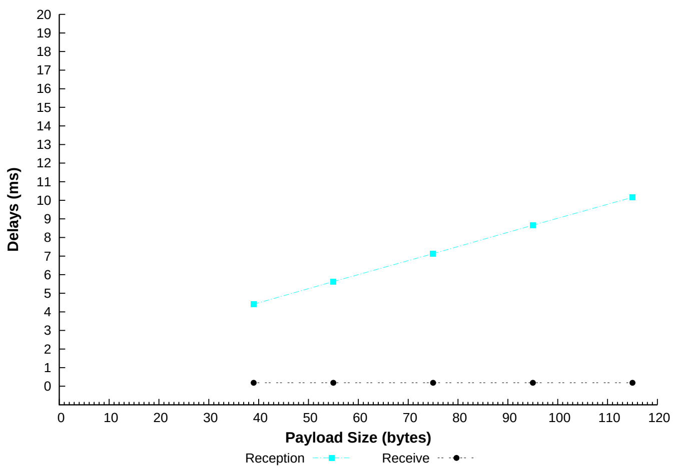


Figure 4.10: Relationships between source receiving delays and payload sizes

Linear relationship between reception delay and payload size is also observed in Figure 4.10. The receive delays are constant for all payload sizes.

Two-way propagation delay

The 32-KHz clock has been used in this experimental study and provides 32,768 ticks per second. There are 32 ticks in one millisecond. Therefore, the finest precision is approximately 0.03125 millisecond or 31.25 microseconds. The two-way propagation delays for all payload sizes are calculated and frequencies of the delay occurrences in ticks are shown in Table 4.10.

Table 4.10: Frequencies of two-way propagation delays

Attribute		Payload Size (bytes)				
		39	55	75	95	115
Frequencies	0	858	807	785	755	740
	1	141	193	212	245	259
	2	0	0	3	0	0
Cycles		999	1,000	1,000	1,000	999

According to Table 4.10, frequencies of the 0-tick decrease with increasing payload sizes. Larger packets require more time to travel from source to destination. However, the two-way propagation delays are significantly less than the other delays.

B) Effects different usage of sources

The main objective of conducting this experiment is to study how different sources affect the delays. Figure 4.11 depicts the experimental scenario and timestamping mechanisms. In total five sources were used in this study. Send command, receive and two-way propagation delays are calculated to investigate any differences in the output.

According to Figure 4.11, fewer delays are calculated compared to Figure 4.8. The base station is booted at x_0. When the base station is ready to send, the `send` command is called at x_1. A timer is used in order to trigger packet transmission. Prior to transmission, the base station sets some fields in the message structure such as its id and transmission power. The SFD transmission occurs at x_2. The timestamp is created and the packet payload content is modified to include the time of the transmission. Therefore, the send command delay of the base station is equal to $x_2 - x_1$.

After being booted at y_0, the source receives the SFD at y_1. The receive event is signalled at y_2 when the source receives the packet. Receive delay of the source is therefore $y_2 - y_1$. Once the packet has been received, the source requires some time to process the information obtained from the packet. It then sets up its own transmission and the bits of packet are loaded into the radio buffer. The `send` command is called at y_3 and the process delay is equal to $y_3 - y_2$. The SFD is transmitted at y_4. Hence, the send command delay of the source is equal to $y_4 - y_3$.

After the packet is transmitted, the base station receives the SFD at x_4. The whole packet is received at x_5. The receive delay of the base station is therefore equal to $x_5 - x_4$. The two-way propagation delay is equal to $(x_4 - x_2)$ - $(y_4 - y_1)$. One Tmote Sky base station and five Tmote Invent sources were used. The source was located at 0.5m away from the base station. The base station was plugged into a desktop computer. The data payload size was 60 bytes. In total 1,000 cycles of message exchange were run for each source. After a node has received the packet, it waits for 128ms and fires the time to start the transmission.

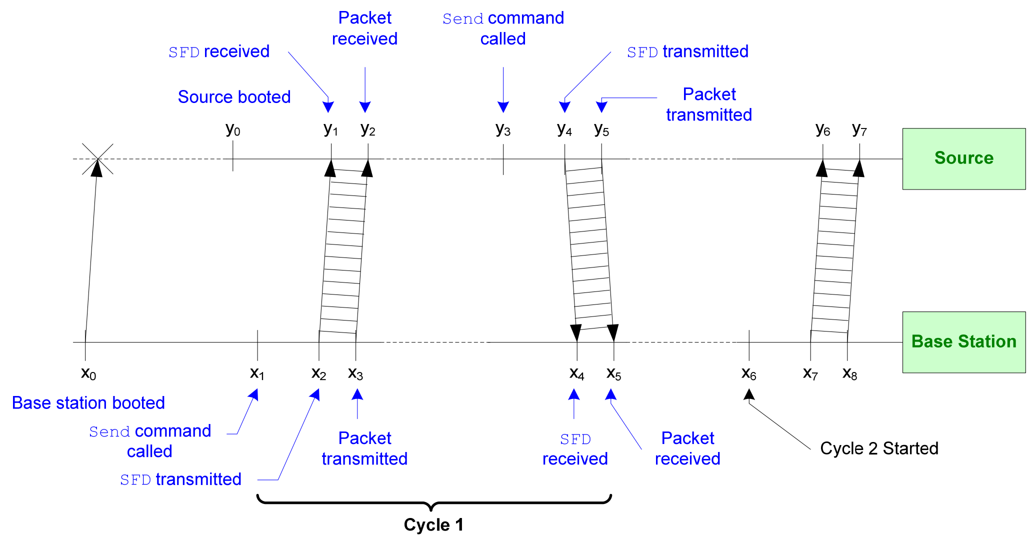
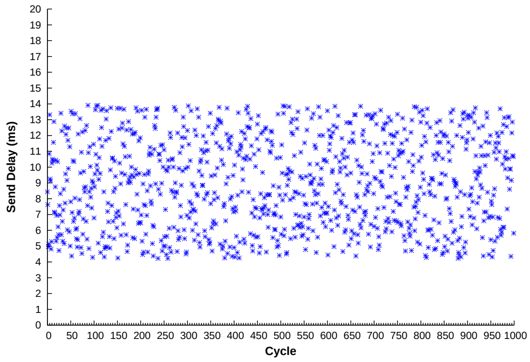


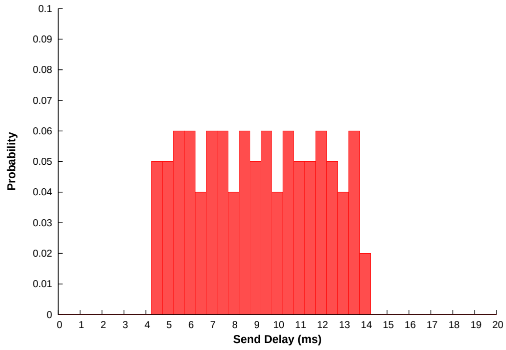
Figure 4.11: Message exchange and timestamping

Send command delay

The send command delay demonstrates the duration required for the SFD to be transmitted after calling the `send` command. Figure 4.12 displays scatter and probability plots of the send delays of Source1 which was also used in the previous study. The delays shown are in milliseconds. In the probability distribution plot, the delay specified at the x-axis is an average value. For example, the 4.5ms is an average of the observed delays between 4.25 and 4.75 milliseconds (ms).



(a) Scatter plot



(b) Probability distribution plot

Figure 4.12: Send delays of Source 1

According to Figure 4.12, the observed send command delays of Source 1 are distributed between 4 and 14ms. The probability distribution plot shows that the output is not a normal distribution. In order to investigate how different sources provide send command delays, the output of all sources is analysed. Table 4.11 shows some statistical analysis of the send command delays of all sources.

Table 4.11: Statistical analysis of send command delays

Attribute		Source				
		1	2	3	4	5
Min		4.22	4.22	4.19	4.19	4.19
Max		13.91	13.91	13.88	13.88	13.91
Percentiles	25	6.59	6.76	6.81	6.42	6.63
	50	8.94	9.34	9.18	8.78	9.03
	75	11.44	11.56	11.41	11.21	11.28
	90	12.94	12.94	12.78	12.84	12.88
	99	13.81	13.81	13.72	13.75	13.75
Cycles		1,000	1,000	1,000	1,000	1,000

According to Table 4.11, the statistical values are insignificantly different between sources. The 50th percentile or median is between 8.78ms and 9.34ms. Minimum and maximum values are approximate 4.20ms and 13.90ms, respectively.

Receive delay

The receive delay demonstrates the required interval for receiving the whole packet by the application. Figure 4.13 shows the scatter plot of the receive delays observed at Source 1.

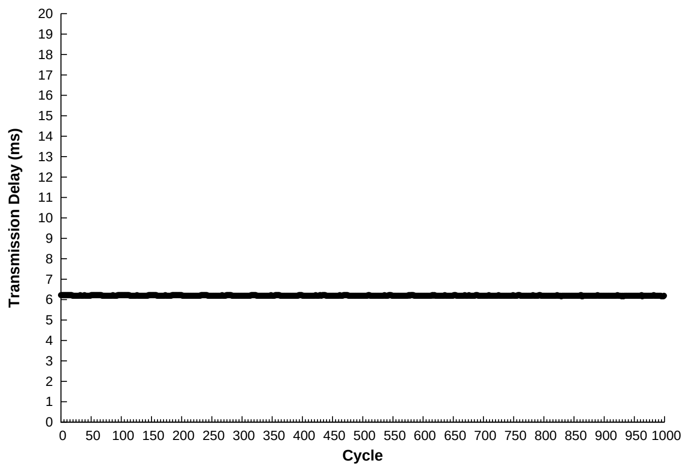


Figure 4.13: Receive delays observed at Source 1

According to Figure 4.13, the receive delays are approximately constant. The delays are between 6 and 6.5 ms. In order to examine whether the results from the other sources are different, some of the statistical measures are summarised in Table 4.12.

Table 4.12: Statistical analysis of receive delays

Attribute		Source				
		1	2	3	4	5
Min		6.16	6.19	6.09	6.13	6.09
Max		6.22	6.22	6.22	6.22	6.22
Percentiles	25	6.19	6.19	6.13	6.13	6.13
	50	6.19	6.19	6.13	6.13	6.13
	75	6.19	6.19	6.16	6.16	6.13
	90	6.22	6.22	6.16	6.16	6.16
	99	6.22	6.22	6.22	6.19	6.19
Cycles		1,000	1,000	1,000	1,000	1,000

The output indicates no significant difference in receive delays between the sources. Sources require at least 6.22ms in order to receive packets.

Two-Way propagation delay

The two-way propagation delays of Source 1 are shown in Figure 4.14. According to Figure 4.14, the results are either 0 or 1 tick. Two-way propagation delays are significantly less than the other delays. However, the zero tick does not always mean zero propagation delay. Table 4.13 indicates the difference in two-way propagation delays in terms of output frequencies.

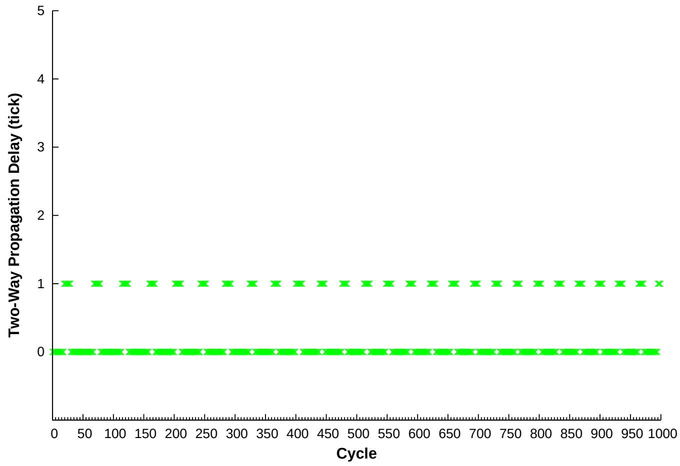


Figure 4.14: Two-way propagation delays of Source 1

Table 4.13: Frequencies of two-way propagation delays

Attribute		Source				
		1	**2**	**3**	**4**	**5**
Frequencies	0	744	817	861	859	882
	1	256	183	139	141	118
Cycles		1,000	1,000	1,000	1,000	1,000

The frequencies of zero tick are greater for all sources. It can be concluded that most of the two-way propagation delays are less than 31.25µs.

In summary, this section aims to describe the measurements of communication delays in WSNs. As the schedule-based MAC approach is adopted in this dissertation, time synchronisation between sources and base station is crucial. A slot is allocated to each of the sources and its size must be big enough to complete the communication. Sending and receiving delays are linearly related to the packet sizes whereas the two-way propagation delay is significantly small. Determination of slot length can be estimated and message transmissions should therefore be scheduled with respect to the sending and receiving events at the Medium Access Control (MAC) layer.

4.6 Conclusion

This chapter has presented several experimental studies and their results which motivate PoRAP (Power & Reliability Aware Protocol) design and development. According to the simulation and experimental results, several conclusions can be drawn as follows:

- The simulation results indicate a high proportion of energy is consumed by the radio communication. This observation demonstrates the importance of reduction in communication energy in WSNs.

- The transceiver's datasheet provides the details of radio power consumption. Whilst the receiving energy is constant, transmission power can be adapted. Transmitting at the minimum instead of maximum power level in CC1000 and CC2420 can conserve over 75% and 50% of power, respectively. Thus, transmission power adaptation is a promising scheme to decrease the communication energy. In PoRAP, the transmission power of the source will be adjusted with respect to the reception strength observed at the base station.

- Received Signal Strength Indicator (RSSI) can be read from both CC1000 and CC2420. Another metric, Link Quality Indication (LQI) is also provided by the CC2420. Both metrics are measured during the reception. An additional reliability related metric, Packet Reception Rate (PRR) is also used. The relationship between RSSI, LQI and PRR is addressed in this research and our results are similar to the observations in [LZZ+06] and [SDTL06]. The RSSI relates to the PRR more clearly than the LQI. The PRR steeply increases with the RSSI followed by a significantly more stable relationship. The RSSI should therefore be used as a basis to determine whether transmission power adaptation is required. Minimum and maximum RSSI are selected from the stable region in the RSSI-PRR relationship as it demonstrates the region where the network should operate. The source is notified to increase its power if the measured RSSI is too low. If too high a RSSI is observed, the base station sets notification of power reduction. The current power is retained if the RSSI is within the desired range.

- There are several models which are proposed to predict the reception strength. According to the analysis and measurements. Such models are not sufficient as they do not capture all effects in the field such as absorption and blocking. The measurements demonstrate that transmission power, distance between sender and receiver, location, heterogeneity in sensor manufacturing and time-of-day affect the reception strength. PoRAP adopts the measurement based scheme in order to accurately obtain the current link quality.

- In PoRAP, notification of transmission power adaptation is broadcast by the base station during the control phase and the sources conduct the adjustment prior to the transmissions. Time synchronisation between sources and base station is crucial in the time-slot based protocol. Sending and receiving delays are linearly related to the packet sizes. The two-way propagation delay is significantly small. Determination of slot length can be estimated and message transmissions should therefore be scheduled with respect to the sending and receiving events at the Medium Access Control (MAC) layer.

In conclusion, the experimental results confirm that the measurement-based approach should be adopted in PoRAP as link quality is affected by several factors. Existing models predicting the received signal strength are not sufficient as they do not capture all effects. The relationship between RSSI and PRR is essential to justify at which the region the network should operate. A lower power can be used for data transmission without further reduction in PRR and a higher power does not result in less data loss. Schedule-based MAC suits the single-hop applications such as environmental monitoring WSNs which require low duty cycle. Communication in PoRAP is represented by a frame which consists of a control slot followed by data slots. The slot size should be big enough to cover both sending and receiving processes and avoid collisions. The linear relationship between delays and packet sizes is useful to estimate the slot length. The scheduling information is also included in the broadcast message and the synchronisation should be conducted with respect to the timestamps performed at the MAC layer.

Chapter 5

PoRAP Design and Implementation

This chapter describes the design and implementation of PoRAP (Power & Reliability Aware Protocol) which aims at minimising communication energy in wireless sensor networks (WSNs). The experimental results stated in previous chapter inform the design and implementation. Functional requirements are listed and some of the existing TinyOS 2.x components are mapped to those requirements. A frame is used to represent the communication cycle in PoRAP. Models are proposed for estimating the slot length together with the awareness of clock drift, so that feasible data collision and communication overlap can be avoided. Time synchronisation refers to the timestamps conducted at the MAC layer. The base station broadcasts the control packet during the control phase. Communication scheduling and power adaptation signaling are included in the control packet. The scheduling is mainly dependent upon the application's requirement whilst the signaling is the result of the comparison between the observed RSSI and the bounds. Data transmissions are performed during the data delivery phase. The source synchronises with the base station by following the predefined scheduling and the notification bits are read and the power is set prior to the transmissions.

5.1 Introduction

PoRAP (Power & Reliability Aware Protocol) consists of three main capabilities. Figure 5.1 depicts such components. Several benefits are provided by addressing the key capabilities.

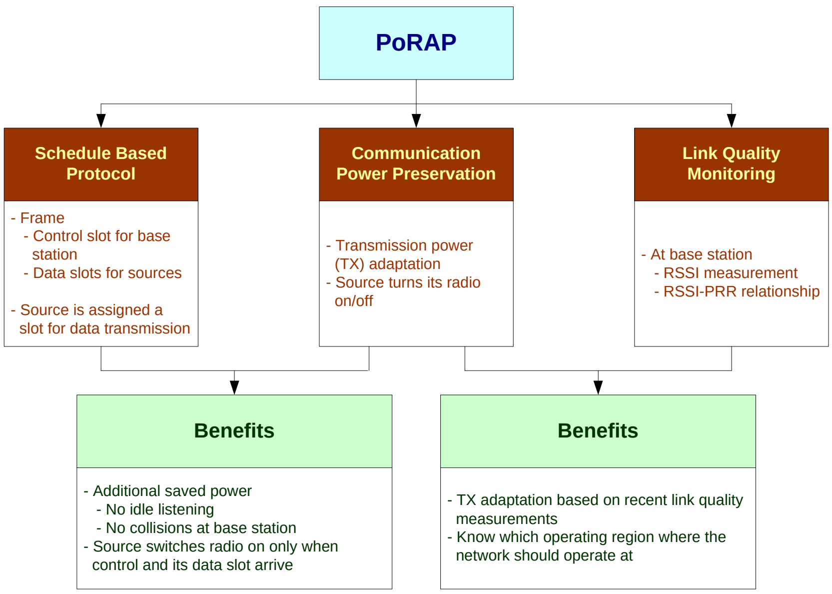


Figure 5.1: Capabilities and benefits in PoRAP

According to Figure 5.1, two main benefits can be achieved by introducing the key capabilities in PoRAP. Firstly, power can be conserved via transmission power adaptation and efficient medium access management. The selected link quality index in PoRAP is Received Signal Strength Indicator (RSSI) and it is measured by the base station during data reception. Along with the awareness of data loss, the adjusted power will often maintain the network operating at the region where data loss is minimised.

Additional communication can be saved by adopting the schedule-based MAC approach. Sending and receiving delays can be estimated as they are dependent upon packet size whilst two-way propagation delay is significantly small. Data transmissions are scheduled and the sources are mostly in sleep mode to conserve energy. Only one source engages the shared medium at a time for data transmission. Thus, data collision can be avoided and idle listening can be minimised. More explanations on PoRAP key capabilities are given as follows:

5.1.1 Schedule-based protocol

In the single-hop networks, sources are capable of communicating with their base station directly. This scenario is feasible when the sources and base station are located within communication range of each other. The base station may be connected to several sensors which require an access to the shared medium. Uncontrolled medium access possibly leads to data collisions at the base station. Collision is one of the main sources of power wastage in the WSN shared medium system. The medium access control (MAC) approach attempts collision avoidance. There are currently two main approaches proposed for WSNs. Firstly, the medium is sensed to detect any ongoing activities in the medium before conducting data transmission and reception. This scheme is named contention-based.

PoRAP employs another approach in which each node is assigned a specific duration to use the shared medium. This scheme is called schedule-based. The other sensors cannot access and use the medium whilst a sensor is communicating within its time slot. Sources listen to the base station only once in a frame. Idle listening is therefore minimised. Moreover, data collisions at the base station can be avoided as there is only one source sending at a time. The slot length should be long enough to let the source and base station complete data transmission and reception. This scheme may not be suitable in the case of multi-hop WSNs where each resource-constrained sensor has to maintain slot information of its neighbours. Furthermore, time synchronisation is required as both sender and receiver have to orchestrate the data communications to avoid collision caused by the other receivers.

Centralised scheduling control by the base station is feasible in PoRAP. Slot arrangement information can be sent to all sensors located in the range. The base station broadcasts a packet to all sources located in its range. Slot information such as number of slots, slot length and start time of first slot are included in the payload. Once the first frame is finished, the base station broadcasts again with the transmission power adaptation notification.

5.1.2 Communication power conservation

Power constraint should be taken into account when designing a protocol for WSNs. Sensors may be left unattended after being deployed in the remote or hostile environment where battery recharge or replacement may be costly or infeasible. Communication accounts for power consumption in WSNs. Several sensor platforms provide adaptation to the transmitting power and the concept of Transmission Power Control (TPC) has been adapted to WSNs. The CC2420 radio employed by Tmote platform, which is used in this research, supports transmission power (TX) setting. The TX levels are stated by a 5-bit number. There are therefore 32 possible TX settings provided by the CC2420. In TinyOS, the `setPower()` command provided by `CC2420Packet` interface accepts a value between 0 to 31 for TX setting. However, the CC2420 datasheet specifies programmable TX in 8 steps from approximately -25 to 0 dBm which are respectively equivalent to the power levels of 3 and 31. The Tmote datasheet follows guidelines given by the CC2420.

Transmission power adaptation policies in WSNs should take application specifics into account. Different applications may require the sources to transmit data at different rates. For example, an environmental monitoring system may require the current temperature hourly whilst a surveillance system may require the data every second when an intrusion is detected. The sensors should be switched to sleep mode after transmission in order to minimise the idle listening. In a multi-hop network, each node is responsible for routing. It has to communicate with its neighbours to discover the best path by means of the least power utilisation. An amount of power is therefore required for listening in the multi-hop. However, a sensor in the single-hop scenario is capable of transmitting data directly to the base station. It may be switched to sleep mode after transmission. However, the source has to listen during the control slot transmission from the base station.

The power adaptation mechanisms in PoRAP do not require historic entries of RSSI and associated transmission power. The main reason is the limitation of buffering capacity of the radio chip. The base station should support a significant number of sources. In the CC2420 radio, the maximum buffer size is 128 bytes. Some bytes are required for the header and other controlling details. Only two bits are used to notify the power adaptation. The RSSI-PRR relationship obtained from the experimental studies is considered for adaptation as it suggests the operating region for WSNs . In the case of power adaptation, the base station sets particular bits to notify the source. The sources get the bits and set their transmission power accordingly.

5.1.3 Link quality monitoring

Radio communication uses air as the transmission medium. There are several attributes ranging from differences in hardware components to environmental factors such as physical barriers which affect signal attenuation. Received signal strength estimation is unlikely as sensors can be placed in various areas of interest. An estimation model should not only determine distance between sender and receiver as an input, location should also be taken into account. A shorter distance may not always provide a higher received strength if a physical barrier appears in the communication line-of-sight (LOS). Moreover, the link quality metrics fluctuate over the time of day. The observed strength in an indoor environment may be lower during the nighttime. Applying the simple received signal strength estimation models, focusing mainly on distance and hardware properties, may not be sufficient. Therefore, PoRAP employs the measurement-based approach in order to more accurately adapt the transmission power.

Two link quality metrics are used in PoRAP. The RSSI is obtained by the radio chip whilst the PRR is specified by the applications. The relationship between RSSI and PRR can relate the application requirement to the observed link quality. As shown in Section 4.4.6, a clear relationship between the two metrics is established. The PRR steeply increases with the RSSI up to a certain point. The PRR is then stable after a certain value of RSSI and a lower RSSI or TX can be used to obtain the required PRR.

The range of required RSSI is obtained from the reliability requirement and the RSSI-PRR relationship. This range is recognised by the base station. Upon data reception, the base station measures the RSSI and compares it to the RSSI thresholds. The adaptation bits are set with respect to the comparison result. There are three available patterns of bit settings; the transmission power will be increased if the measured RSSI is lower than require and it will be decreased if the RSSI is higher. The sources will be notified to retain the current power if the RSSI is within the range.

5.2 Functional Requirements

Four main functional requirements of PoRAP development are listed as follows:

1. *Transmission power conservation*: As communication power accounts for a significant proportion of energy consumption, PoRAP adapts the transmission power (TX) of the sources or sensors in order to reduce this power. The Received Signal Strength Indicator (RSSI) is used to demonstrate current link quality. The RSSI can be measured at the receiver which employs any radio chips such as the CC1000 and CC2420. No additional hardware or software implementation is required for the measurement. An optimal power will be used whilst reliability is still achieved. There may be lower transmission power levels which provide reliability within the desired range.

2. *Operating at the right region where transmission power adaptation does not compromise required reliability:* WSNs are application specific. Apart from RSSI and/or LQI, Packet Reception Rate (PRR) should be used as an additional link quality metric as it is close to the reliability requirement. A relationship between RSSI and PRR is established and it can be used to justify which region the network should operate at. The sources may transmit at a lower power level and a low RSSI may be obtained. Transmission power can be conserved but the observed PRR may vary highly. According to Figure 4.7(a), the sources should operate at the region which provides the RSSI higher than -85 dBm to avoid the high variation in the PRR.

3. *Power in a shared medium access system:* In single-hop WSNs, the base station may communicate with a significant number of sensors. Upon receiving packets from all sensors, collision at the base station must be effectively avoided. The schedule-based approach is adopted where a slot is assigned to each sensor. The key concept is to allow only one sensor to communicate with the base station at a time. Furthermore, idle listening is also important. The sensor can be switched to sleep mode after transmission. Power used for idle listening can be minimised. Other sources including overhearing and overemitting can be mitigated as the other sources are in sleep mode when the medium is engaged. Slot length determination is also crucial in this requirement. It should be long enough to cover sending and receiving data by source and base station. Several delays are the key aspect to consider for determining the slot length.

4. *Robustness*: As PoRAP adopts the schedule-based scheme, the network setup phase is required for the base station to discover its sensors. The base station firstly broadcasts its control packet to all sources located in its communication range. The sources obtain control information in the payload and initiate transmission only when their slots arrive. The scheduling details can be used by the sources. In PoRAP, transmission power adaptation is also supported. This can be done by including the notification for each node in the control payload. In PoRAP, a few bits are used for the notification per source. Therefore, the base station is able to support a significant number of sensors. After all the sensors have transmitted, the base station broadcasts again to minimise the accumulation of clock drift.

According to the above requirements, in total three considerations should be taken into account. Firstly, transmission power policies should be addressed. The adapted power must not be lower or higher than the minimum or maximum level provided by the radio unit. Secondly, the relationship between RSSI and PRR should be considered. It can be used for setting the RSSI thresholds including the minimum and maximum values. The transmission power will be increased if the measured RSSI is lower than the minimum and it will be decreased if the RSSI is higher than the maximum. The current power will be retained if the observed RSSI is in the desired range. The RSSI thresholds should be in the region which produces stable PRR. Finally, scheduling arrangement and maintenance require data exchanges between sources and base station. Time synchronisation is a key requirement in the schedule-based approach. Clock drift will occur as local clocks are running at different speeds and it will cause faulty synchronisation. The processes should be periodically repeated in order to avoid significant accumulation of the drifts to maintain the synchronisation. Timestamps at various command calls and events are performed to investigate several delays and specify the appropriate slot length.

5.3 PoRAP Architecture

This section aims to describe PoRAP architecture. PoRAP aims at an efficient data delivery in WSNs by means of energy conservation. Input of PoRAP comes from two external components, the user/application and the monitored phenomenon. PoRAP recognises the duty cycle and the awareness of data loss. The sensed data is another input and it will be sent from the source to the base station. In order to achieve the goals, the base station controls the sources whereas the sources send data to the base station. Required functionalities of the base station and the sources are then stated. The interactions between them are described and they are used to address the required components within the source and the base station. Moreover, the interactions between such components are also given in this section.

5.3.1 Overview of PoRAP

The main objective of PoRAP development is to provide an efficient data communication in wireless sensor networks (WSNs) where the user/application has his/its own requirements such as reliability and duty cycle. The development of a generic network protocol for WSNs is challenging as WSNs are application specific. Figure 5.2 shows an overview of PoRAP architecture in terms of the interactions between its main components.

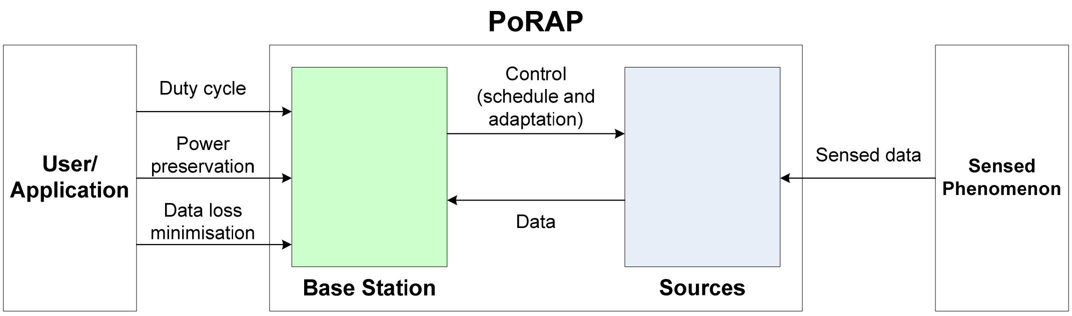


Figure 5.2: Overview of PoRAP

According to Figure 5.2, four main components are addressed including the user/application, sensed phenomenon, base station and sources. As WSNs are application specific, the user/application has its own set of requirements. The base station directly interacts with the user/application whilst the sources collect physical directly from the phenomenon. The functionalities required at the base station and source can be listed as follows:

Base station:

- **Recognise the requirements of user/application:** PoRAP aims at the low duty cycle application where the key objective is power conservation instead of throughput. Examples of this application category are habitat and environmental monitoring systems.

- **Control the source's operation:** This dissertation focuses on the single-hop network where direct communication between sources and base station is feasible. No routing is required at each source and its operation is controlled by the base station in two aspects. Firstly, the base station determines whether transmission power used by the source needs to be adjusted by looking at the RSSI. Secondly, the communication cycle of each source is scheduled in order to avoid data collision and minimise idle listening.

Source:

- **Collect physical data:** WSNs have been deployed to collect physical data from the targeted environment such as temperature and humidity. This dissertation looks at how an efficient data delivery can be achieved by using lower transmission power whilst data loss is minimised. The processes of data collection are outside the scope of this study.

- **Data transmission:** After receiving the control information, the source sets two parameters. Firstly, it synchronises the communication schedule. Thus it will know when to start the radio for control reception and data transmission. Secondly, the source adapts its transmission power level according to the included notification. Lower power can be used and a significant amount of transmission power can be conserved.

Several interactions between the source and base station are required to achieve the functional requirements and they are addressed in Figure 5.3.

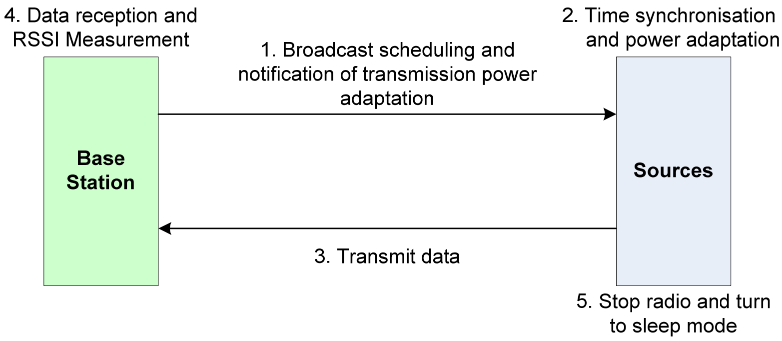


Figure 5.3: Interactions between source and base station

1. PoRAP focuses on the set of fixed sources which are located within communication range of the base station. The control packet includes scheduling and power adaptation notification and is broadcast to the sources using the maximum power level. This is feasible as the base station obtains extra power from the connecting computer.

2. Once the control packet is received by the source. Information on scheduling and notification is read. The source synchronises its schedule with the other nodes together with adjusting its transmission power accordingly.

3. After conducting time synchronisation and transmission power adaptation, the source waits for its slot to conduct data transmission using the adjusted transmission power. The radio must be started for communication.

4. The base station measures the RSSI during data reception. The observed RSSI is compared to the desired range which includes minimum and maximum values. The setting of the RSSI thresholds is obtained from the RSSI-PRR relationship. The selected RSSI should be obtained from the region where significant stability in the PRR is observed. The base station then decides whether transmission power adaptation is required. The notification is set accordingly.

5. The source stops its radio after transmission to save power. The amount of power consumption is the least when the source is in sleep mode. Timing is required for the source to start the radio again for the next communication cycle.

5.3.2 Components

The previous section points out several essential functions which are required to achieve the objectives of PoRAP development. This section aims to describe the essential components which give rise to this functionality. The selected operating system for WSNs in this dissertation is

TinyOS which already provides several useful components and PoRAP takes those in TinyOS and adds some further modifications. The main components are determined from the interactions including the user/application, the observed phenomenon, the base station and source. Several components required at the base station and source are then considered. Moreover, the interactions between each component are demonstrated.

A) Components at base station and sources

The base station recognises the requirements of the user/application and controls the sources based upon the requirements. As PoRAP aims at the direct communication, the control information is broadcast to the sources which are located within the communication range. After physical data collection, the sources set their communication parameters prior to data transmissions. Figure 5.4 depicts several components required at the base station and sources.

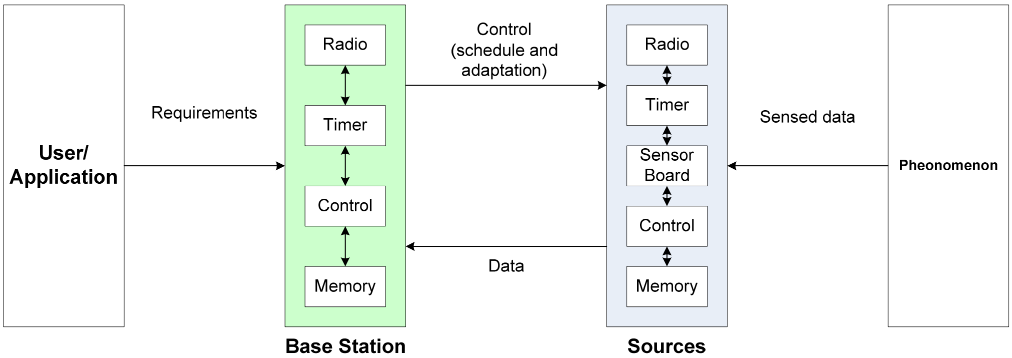


Figure 5.4: Components at base station and sources

Each of the required components is described as follows:

- **Radio:** Each sensor employs the radio communication for wirelessly communicating with its neighbours or destinations. The radio has four major functions as follows:

    - *Data communications:* Control information is sent by the base station's radio chip and is received by the source's radio chip. Data is sent by the source's radio chip and is received by the base station's radio chip.

    - *Data buffering:* Prior to forwarding the received data to the higher layers or transmiting the data through the medium, the data is buffered. The buffering capacity is limited and dependent upon the radio chip. The capacity is important to the design of packet structures. For example, the control packet must not be longer than the allowable capacity but it has to carry all the required information.

- *Received signal strength measurement:* The received signal strength is important as it can reflect the current link quality. The latest radio chip provides the measurement of received signal strength such as Received Signal Strength Indicator (RSSI) and Link Quality Indication (LQI). RSSI is used in this dissertation as it can be obtained from several radio models and its relationship with the Packet Reception Rate (PRR) is clear.

- *Transmission power adaptation:* The RSSI changes with transmission power and several factors such as location, time-of-day and environment. One of the main features in PoRAP is transmission power adaptation. The key concept is adjusting the current transmission power to achieve the power conservation and data loss minimisation. The latest radio model supports programmable transmission power.

- **Timer:** WSNs are considered a share-medium system as all nodes have to access the medium prior to transmission. PoRAP aims at single-hop WSNs where direct communication between source and base station is feasible. The sources are not responsible for routing. Instead of applying the contention-based scenario, the transmissions are scheduled. A slot is allocated for each source so that it can send only when its slot arrives. Otherwise, the radio is stopped and the source is switched to sleep mode for minimum energy consumption. A timer is therefore required for scheduling the radio start and stop.

- **Control:** It is used to control the other components especially when there is no control mechanism provided for some components. For example, an additional control interface is required for the radio and the interface is used to start and stop the radio.

- **Memory:** This component is the basic one which is also included in the sensor. Several variables along with their values and measurements are stored in the memory. For example, the required RSSI range which is obtained from the RSSI-PRR relationship. This range is stored in the memory and will be compared to the observed RSSI to determine whether any transmission power adaptation is required.

- **Sensor board:** This component is crucial for the sensors as it is responsible for collecting the physical data from the environment. The sensor board consists of several sensors such as temperature and humidity.

B) Interactions between components

This section aims at addressing the interactions between the components, and they are described in Figure 5.5. The interactions within the base station and source can be separately described as follows:

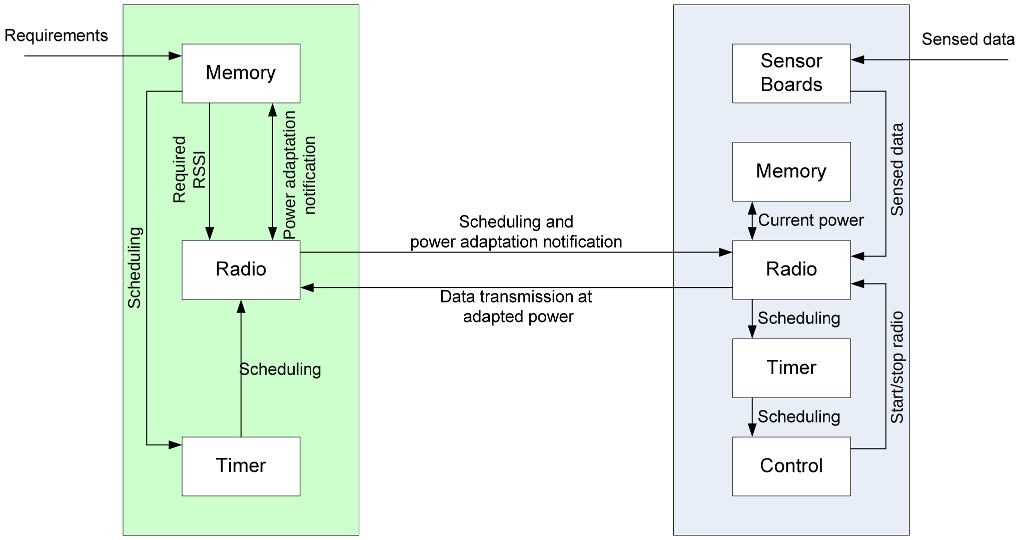


Figure 5.5: Interactions between components

Base station

The base station acts as a destination for the data. The requirements are stored in the memory and they are used to set required RSSI range and the data sending rate. In PoRAP, the schedule-based scheme is adopted where each source has its own slot for data transmission. The slot must be large enough to accommodate several communication delays. According to the results in Chapter 4, sending and receiving delays are mainly dependent upon the packet size whereas the two-way propagation delay is significantly small. Models are required for estimating the slot size and they will be described later in this chapter. The next transmission begins after the other sources have already transmitted. Hence, PoRAP suits the applications which require a low duty cycle. The timer is used for scheduling the communications so it also uses this requirement from the application.

The required RSSI range can be obtained from the RSSI-PRR relationship which is dependent upon different conditions such as time-of-day, environment and location of deployment. The PRR is also used as an additional link quality metric as it is close to the reliability requirement. The main objective of PoRAP is to conserve communication energy whilst data loss is minimised. In the short term, the base station measures the RSSI when it receives the data packet. It uses the observed RSSI to determine whether power adaptation is required. The notification bits which are reserved for each source are then set. In the medium or longer term, the base station measures the PRR and uses that to determine what the upper and lower RSSI bounds should be. If more packets are lost, the RSSI bounds are increased. However, the bounds are slowly lowered to reduce power expenditure if the loss is low or non-existence. The number of notification bits is crucial as the base station has to communicate with all the sources in its range. Using too many bits may lead to a control packet which is larger than the buffering capacity of the radio chip.

The base station radio is not started or stopped as it has to continually receive the data packets from its sources. Data packet receptions occur after broadcasting the control packet at the maximum transmission power level. This concept is feasible as the base station has an extra source of power from its connecting computer. In PoRAP, the power conservation goal is mainly located at the sources.

Source

In WSNs, the source is responsible for physical data collection. The data is then transmitted to the base station. The key objective of PoRAP is to conserve communication power of the source. Prior to transmission, the source determines whether it has to adapt its current power. The notification is included in the control packet and it is received by the radio of the source. As the buffering capacity of the radio is limited, the base station notifies what the source should do to its current power instead of specifying the appropriate power level. Thus, the source has to store the current power in the memory. For example, the current power is increased if a lower RSSI is measured by the base station. Moreover, the source should recognise the limitations of the transmission power adaptation. The base station may need its source to increase the power even if the maximum has already been reached. The minimum and maximum power levels are dependent upon the selected radio chip.

Apart from the power adaptation signaling, the scheduling is also included in the control packet. Time synchronisation is crucial in the schedule-based approach. The local clock of each node may run at different speeds. In PoRAP, the sources synchronise with their base station. The synchronisation refers to several timestamps which are conducted at the MAC layer where hardware and operating system dependent delays can be disregarded. The scheduling is also recognised by timer and controls components. Several timers are required as they are responsible for timing the sending and receiving communications. The timers operate closely with the control in order to start and stop the radio. For example, the radio is stopped after the data packet is sent. The source knows when it has to wake up to receive the next control packet. The timer is then started, counting the generated ticks. A control interface is used to start the radio for control reception when the scheduled time has come.

5.4 Transmission Power Adaptation Policies

A sensor consists of hardware components working together to facilitate sensing, processing and communicating tasks. Amongst these components, the transceiver or radio unit is responsible for data communication. Normally, the radio unit supports programmable transmission power and the possible adaptable range is given in the datasheet. For example, the Tmote sensor platform which is chosen for this dissertation employs the CC2420 radio. The minimum and maximum powers are 0 and -25 dBm, respectively. In TinyOS, the `CC2420Packet` interface provides the `setPower()` command which accepts a range of 1 to 31 of TX levels. This section aims at providing the policies of transmission power adaptation which depend upon any limitation in the hardware or operating conditions.

5.4.1 Consideration of transmission power bounds

Let tx_{min} and tx_{max} represent the minimum and maximum powers allowed by the radio unit. The first power adaptation policy is given in Equation (5.1).

$$tx_{min} \leq tx \leq tx_{max} \tag{5.1}$$

The base noise is defined as the strength in dBm measured at the receiving node when the node has no data reception in progress. Therefore, the sensor has to transmit at the power which produces a received strength higher than the base noise as shown in Equation (5.2).

$$tx \geq \mathit{base\ noise\ at\ receiver} \tag{5.2}$$

Finally, the transmission power should be greater than the summation of the receiving power and the attenuation. The environmental factors such as climatic conditions and physical barriers crucially affect the attenuation which should be measured during the operation phase. The transmission power will be adapted accordingly.

$$tx \geq (\mathit{required\ rx} + \mathit{attenuation}) \tag{5.3}$$

The rx is the receiving power. According to Equation (5.1) to (5.3), the upper limit of transmission power is demonstrated by the allowable maximum power which equals 0 dBm, or transmission level of 31 for the Tmote platform. However, the lower limit consists of 3 attributes including the minimum power, the base noise at the receiver and the summation of the required receiving power and attenuation. The maximum of the three attributes should be used as lower limit (tx_{low}) as shown in Equation (5.4).

$$tx_{low} = max\ (tx_{min}\ ,\ \mathit{base\ noise\ at\ receiver,\ required\ rx} + \mathit{attenuation}) \tag{5.4}$$

In summary, there are two main factors which should be taken into account when transmission power adaptation is required. Several hardware limitations of the radio unit include the allowable minimum, maximum transmission power and base noise. The environmental factors leading to signal strength attenuation should be determined. The selected transmission power should be high enough to produce the associated receiving strength which is not discarded by the receiving node. The maximum power allowed by the radio unit is used as the upper limit. In PoRAP, sources use maximum power for their first transmissions. This policy ensures that the packets will likely be transmitted to the base station. However, both base noise and attenuation are respectively hardware and environment dependent. It is difficult to specify an accurate power adaptation level which can be generally used. Moreover, additional resources will be required if the sources periodically measure and send their base noise to the base station. Attenuation is hard to predict as link quality changes over time. Hence, PoRAP repetitively increases or decreases the transmission power within an allowable range instead of discovering the right power.

5.4.2 Operating region and determination of RSSI bounds

The reliability-related metric used in PoRAP is Packet Reception Rate (PRR) which is defined as a percentage of the ratio of the number of correctly received and sent packets. Apart from PRR, RSSI is also used in PoRAP. The relationship between RSSI and PRR obtained in the previous chapter and the literature, as in [LZZ+06] and [SDTL06], is useful to decide the suitable region where the network should operate efficiently. The PRR steeply increases with the RSSI followed by a stable period. Hence, the network should avoid operating at the steep slope as a fluctuating PRR may be obtained.

Transmission power and RSSI are linearly related [LZZ+06]. After a certain point, an increase in transmission power may not significantly improve the PRR. A lower power can be used for data transmission and some power can be conserved. A RSSI range is defined by considering the RSSI-PRR relationship. The lower and upper bounds of RSSI are recognised by the base station. The RSSI is measured and compared to the bounds. The transmission power will be decreased if the RSSI is higher than the upper bound. In the case where the measured RSSI is lower than the lower bound, the power will be increased. No change to the current power is required if the RSSI is within the range.

Power adaptation is notified by setting a few bits in the control payload. The key reason of establishing adaptation bits is a limitation in the payload size in the radio communication. The CC2420 is a byte radio and its buffer capacity is limited to 128 bytes. The header of the standard `message_t` structure used in TinyOS 2.x is 11 bytes. The maximum payload size is therefore approximately 117 bytes. Whole byte usage for power adaptation notification results in a very limited number of supported sources. Details of adaptation bits are given later in this chapter.

The determination of RSSI bounds can be used in the short-term as the PRR monitoring may take a significant duration. A communication cycle where each source transmits only once does not provide sufficient information on whether a transmission power adaptation is needed. This is because either 0% or 100% of PRR will be obtained. Another policy can be used for the long-term data delivery where the base station is able to count the number of received and transmitted data packets. The link quality changes over time and the RSSI bounds should be amended accordingly. For example, the RSSI bounds should be increased if the measured PRR is decreased. This means that higher transmission power is required for increasing successful data delivery. However, the RSSI bounds should be lowered if the PRR is increased or unchanged. This strategy can conserve communication energy as a lower transmission power will be used.

5.5 Estimation of Communication Delays and Frame Structure

A schedule-based approach is adopted in PoRAP. The base station allocates and manages several time slots. In this dissertation, a set of fixed nodes is determined. The number of data slots is therefore equal to the number of booted sources which are able to receive the control packet broadcast by the base station. The source initiates transmission when its assigned slot arrives. Apart from data slots, a frame also contains a control slot which is used by the base station. The slot must be large enough to accommodate sending and receiving delays to avoid feasible data collisions. As shown in Section 4.5.2, the delays are dependent upon packet sizes. This section analyses these relationships and several models are proposed for delay estimations. Moreover, frame structure and format of slots are described.

5.5.1 Communication delays

Delays are investigated in order to determine the appropriate slot length. Several sources of message delivery delay are described in this section. Prior to data transmission through a wireless medium, several tasks are required. The packet is prepared and delivered to the CC2420 or radio unit by the application. The `send()` command is called when the timer is fired. This feature enables send scheduling. Once the SFD (Start of Frame Delimiter) is detected by the CC2420, the `transmittedSFD()` event is signaled by the radio. The packet is then buffered and transmitted through the medium.

At the receiving side, the SFD is received and the `receivedSFD()` event is signaled by the CC2420. The packet is received and buffered. The packet is then delivered to the application and its `receive()` event is signaled. The sources of delay outlined by [GKS03] and [MKSL04] are described as follows:

1. *Send delay*: This is the duration required for message generation at the application layer. A sending request is also issued to the MAC layer. The duration also includes the delay for reaching the MAC layer and the radio unit. The operating system performance mainly affects the send time.

2. *Access delay*: The access delay is considered to be from the free medium detection until the transmission initiation by the radio unit. This duration mainly depends upon the current volume of network traffic and the deployed MAC protocol. Note that this delay applies to contention based protocol. Thus, it is not included in PoRAP.

3. *Transmission delay*: This is the time taken by the radio at the sending side to transmit the message. Message length and speed of the radio are the two main factors for transmission time consideration. This research uses the Tmote platform employing the CC2420 radio which sends $250 * 10^3$ bits per second (bps). The maximum payload size allowed by the CC2420 is approximately 117 bytes. The desired duration is therefore in milliseconds. Theoretically, the packet with 117-byte payload size will take 3.75 milliseconds.

4. *Propagation delay*: This is measured after the message has left the sender. The propagation time depends upon the distance between the two nodes. According to the speed of light, less than 1 microsecond is taken for the distance under 300 metres which is greater than both the indoor and outdoor transmission ranges of the Tmote platform [CC2420]. This delay is considerably less than the others and it may be therefore neglected [GKS03]. The two-way propagation delay requires a complete message exchange where the packet is returned to the sender. It is equal to the difference between the SFD detections conducted at the sender and receiver.

5. *Reception delay*: The reception time is the time required to receive the message by a radio unit.

6. *Receive delay*: This is the time required to process a received message to the application. The current time when the `receive()` event is signaled at the application can be used to compute this delay.

Amongst the described six sources, the transmission, and reception and propagation delays can be considered deterministic by analysing the payload size. The propagation delay is significantly smaller than the other delays. The send and receive delays depend upon the operating system performance. The application uses some components and interfaces to send/receive messages to/from the MAC layer and the radio unit. TinyOS performs additional tasks to complete the requested calls. The medium access is performed by the MAC layer. Network traffic crucially affects the access time which may take seconds.

5.5.2 Frame structure and slot composition

In PoRAP, a frame is used to represent a communication cycle which consists of one control slot at the beginning followed by several data slots. Its structure is shown in Figure 5.6.

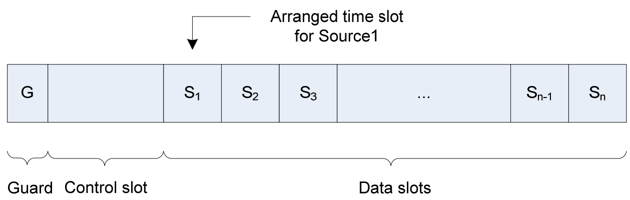


Figure 5.6: Frame structure

G indicates the guard of the frame and is used to protect frame overlapping. A control slot is used by the base station for broadcasting control data which includes scheduling information and transmission power (TX) adaptation notification to its sources. The slot information is required by the sources in order to synchronise themselves to the base station. The time of starting the first data slot is required so that the sources know when data is sent. In PoRAP, each slot has the same length which should accommodate a specific data payload size to be completely transmitted and received.

According to Figure 5.6, the sources firstly turn their radios on during the control slot to receive the control information. If they are not assigned to the first data slot, they stop the radios after knowing when their slots start. When their slots arrive, the radios are re-started to send the data. Unlike sources, the base station listens to the medium for data packet reception all the time. The dformat of a slot is depicted in Figure 5.7.

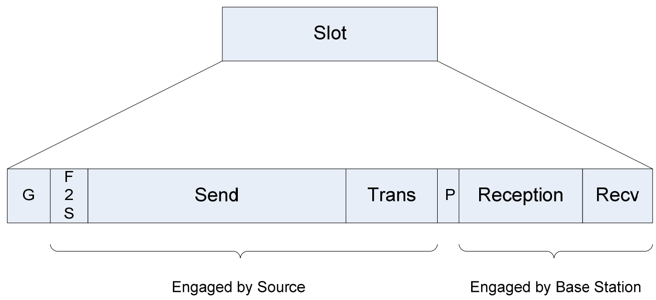


Figure 5.7: Data slot decomposition

There are four main delay components in Figure 5.7. The *G* and *P* are respectively the guard time and propagation delay. The first component is the guard length which prevents the slots from overlapping. Feasible overlapping scenarios together with guard time consideration are provided later in this section. The second component consists of fire-to-send (F2S), send and transmission delays and this is the sending delay component. This component is caused by the source. The third one is propagation delay which is considerably smaller than the other delays. Finally, the receiving delay component includes the reception and receive delays. This component is considered during packet arrival at the base station.

5.5.3 Linear Regression analysis on communication delays

The experimental results on delays described in Chapter 4 demonstrate linear relationships between delays and data packet sizes. The key objective in this part is to discover the two coefficients obtained from linear regression analyses. The coefficients will be used to establish the models providing estimated delays where payload sizes are input.

In total 5 payload sizes including 39, 55, 75, 95 and 115 bytes were varied to investigate changes in delays. Regression analyses have been applied to the results of the sending and receiving delays of the source and the base station. As linear relationships between delays and payload sizes are observed, two coefficients of the linear equation (c_0 and c_1) are the required output where c_0 is the y-intercept and c_1 is the slope. The generic form of models is shown in Equation (5.5). Table 5.1 summarises the coefficients of each delay.

$$Delay = c_0 + c_1\ (payload\ size) \tag{5.5}$$

The units of delay and payload size are respectively milliseconds (ms) and bytes. Table 5.1 shows the coefficients of linear regression analyses of experimental results at 99th percentile. According to Table 5.1, the coefficients for the base station do not significantly differ from those for the source. The fire-to-send delays of the base station are constant whilst the source provided a linear relationship.

In the case where the payload size is zero, a specific duration is still required for header transmission and reception. For CC2420, the header is approximately 11 bytes and requires 0.352ms for the delivery. An additional duration is required for transmitting processes which can be considered as an overhead. The send delay is the largest of the experimental results. It is an interval from calling the `send()` command until capturing the SFD. Several mechanisms undertaken by the application software and operating system to facilitate the sending also require time and are included in the send delay. For example, when the `send()` command is called by the application, an interrupt is signaled to TinyOS. The packet is buffered and the CC2420 is switched to transmitting mode. This sending overhead due to software manipulation and hardware setup is regardless of payload size.

Table 5.1: Coefficients obtained from experimental results at 99th percentile

Delays	Measured at	Coefficients	
		c_0	c_1
1. Fire-to-send (F2S)	Base station	Constant delays of 0.50 ms	
	Source	0.204	0.025
2. Send	Base station	11.367	0.043
	Source	11.263	0.043
3. Transmission	Base station	0.490	0.033
	Source	0.552	0.033
4. Reception	Base station	1.521	0.076
	Source	1.521	0.076
5. Receive	Base station	Constant delays of 0.22 ms	
	Source	Constant delays of 0.22 ms	

Increases in payload size require additional delays. For example, for every byte increase in the payload size, the send and reception delays of a source respectively increase by 0.043 and 0.076ms. However, the payload size does not affect receive delay.

5.5.4 Models for delay estimation

In this section, several models are proposed for estimating sending and receiving delays with respect to input payload sizes. Sending delays include fire-to-send (F2S), send command and transmission delays whilst receiving delays include reception and receive delays. In each delay, the coefficients of source and base station are obtained and the maximum values shown in Table 5.1 are used.

A) Decomposition of sending delay

There are three components in the sending delay and they are described as follows:

1. *Fire-to-send (F2S) delay*: This represents the interval required after a timer is fired. The timer is used to schedule the transmission. After it is fired, the source sets its parameters such as id and transmission power into the payload. The `send()` command is called after all parameters are set. The F2S delay is expressed in Equation (5.6). The payload size is represented by *p*.

$$F2S\ delay\ =\ max((0.204 + 0.025p,\ 0.50) \qquad (5.6)$$

2. *Send command delay*: This is the duration from the `send()` command being called until the SFD (Start of Frame Delimiter) is transmitted at the MAC (Medium Access Control) layer. Equation (5.7) shows the send command delay.

$$\textit{Send command delay} = 11.367 + 0.043p \tag{5.7}$$

3. *Transmission delay*: This is the duration from the SFD transmission until the `sendDone()` event is signaled by the application layer. Equation (5.8) represents the transmission delay.

$$\textit{Transmission delay} = 0.552 + 0.033p \tag{5.8}$$

According to Equation (5.8), one additional byte transmission requires 0.033ms. The CC2420 radio provides the data rate of 250kbps, or it takes approximately 0.032ms for sending a byte of message. In total 0.585ms is required for a 1-byte data payload. By taking the CC2420 header of 11 bytes into account, a 12-byte packet takes 0.585ms, or approximately a 65% data rate (12*8/0.585 = 164kbps) is achieved.

B) Decomposition of receiving delay

There are two components in the receiving delay and they are described as follows:

1. *Reception delay*: It represents the interval from the SFD being received by the radio unit until the `CC2420Transmit.sendDone()` event is signaled by the radio. The reception delay is expressed in Equation (5.9).

$$\textit{Reception delay} = 1.521 + 0.076p \tag{5.9}$$

By comparing Equation (5.9) to (5.8), the reception delay is greater than transmission delay. As the Tmote Invent and Sky employ the CC2420 radio, they should be equal. An additional duration is required for the radio before signaling the `CC2420Transmit.sendDone()` event.

2. *Receive delay*: This represents the interval required for delivering the message to application layer. The receive delay is expressed in Equation (5.10).

$$\textit{Receive delay} = 0.22 \tag{5.10}$$

The receive delay is constant at 0.22ms and is hardware dependent.

C) Propagation delay

According to the results, the maximum two-way propagation is two ticks which is much less than 1ms. Most of the outputs are either 0 or 1 tick. The propagation delay is therefore very small compared to the other delays. A 1ms is reserved for the two-way propagation delay in this research.

D) Guard time length determination

A schedule-based protocol requires an acceptable clock accuracy. Clock drift is an important aspect which should be considered. A guard time aims to avoid an overlapping between slots while their durations are dependent upon the sources' local clocks. An additional duration is required for accommodating the clock drift impacts.

The Tmote platform employs a MSP430 F1611 microcontroller from Texas Instruments. The MSP430's clock system consists of three clock signals generated by ACLK (Auxiliary Clock), MCLK (Master Clock) and SMCLK (Sub-Main Clock). The microcontroller provides low power modes where some or all of the modules are disabled for power conservation. The LPM3 (Low Power Mode 3) is used in the Tmote platform and ACLK is the only operating clock in the LPM3. The ACLK uses a 32-KHz watch crystal to generate oscillations and it has clock drift of 20ppm (part per million). The clock drift should not be neglected as sensors may be running for a long period and the drift may accumulate into seconds. The clock drift is crucial in determining guard length.

Figure 5.8 demonstrates a scenario where slot overlapping occurs.

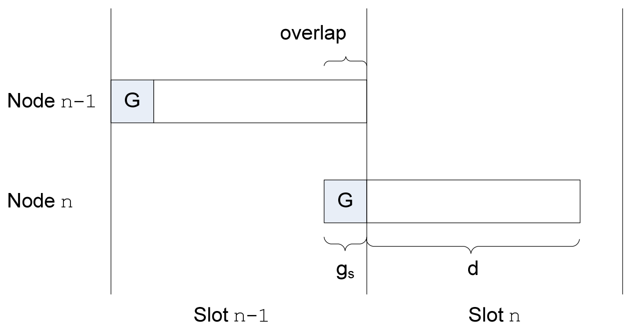


Figure 5.8: Overlapping of slots

The g_s and d respectively denote guard length and the remaining part of slot. There may be a case where the clock of Node n runs more quickly than the other clocks. The node misunderstands that its slot has arrived and the packet is transmitted too early. Hence, an overlap has occurred.

According to Figure 5.8, the total slot length is equal to (g_s + d) ms. Prior to the packet of Node n being transmitted, a total of (n-1) slots have been processed. The g is required to be greater than or equal to 20ppm. The duration taken by (n-1) slots is (n - 1) times (g_s + d). The drift caused by such slots is shown in Equation (5.11).

$$Drift = (n -1)(g_s + d)(20 * 10^{-6}) \tag{5.11}$$

Equation (5.12) demonstrates the required guard length.

$$g_s \geq (n -1)(g_s + d)(20 * 10^{-6}) \tag{5.12}$$

According to Equation (5.12), the term g_s $(20 \text{ x } 10^{-6})$ is significantly less than g_s. The above equation can be rearranged and displayed in Equation (5.13).

$$g_s \geq (n -1)(d)(20 * 10^{-6}) \tag{5.13}$$

The required guard length is therefore dependent upon the length of the remaining part of the slot (d) and number of allocated slots (n). According to Equation (5.13), a 1-ms gap can accommodate the product of $(n -1)(d)$ up to 50,000. Assuming that there are 100 allocated slots, the reserved 1-ms duration is capable of accommodating the slot length of 500ms which is significantly greater than the duration required for transmitting and receiving the maximum packet size limited by the CC2420 radio.

5.5.5 Proposed slot length

Previous sections discuss the durations required for sending, receiving, clock drift and two-way propagation delay. Slot length is considerably dependent upon the size of the data payload. This section aims to describe the proposed slot length.

Two assumptions in the determination of slot length apply. Firstly, system initialisation is required for sources and base station. The sources listen and receive the control packet from the base station. The listening period is thus the duration required for the base station to prepare its packet prior to transmission. Secondly, the durations required for transmitting and receiving the same piece of data by the radio are equal. Several command calls and event signals in TinyOS can be used to measure delays. Some of them are non-deterministic whilst the others can be computed by looking at the hardware specification and the radio communication characteristics.

A) Determination of clock drift

Apart from communication delays, clock drift is also important in a schedule-based approach like PoRAP. Time synchronisation cannot be maintained if an interval is not sufficiently reserved for the drift. Each sensor consists of an oscillator which generates a timing signal or tick. The difference in the oscillator manufacturing process results in different speeds of signal generation. Time synchronisation often assumes that the local clocks of nodes are running at the same speed. When clock drift occurs, time synchronisation is no longer maintained.

There are several sources of clock drift. The duration between two consecutive transmissions is another important factor apart from hardware characteristics. A set of experiments focusing on clock drift measurements is therefore required. This is described in Section 6.4. A 20 part per million (ppm) is recommended for clock drift in [CMR200]. The results will be compared to the suggested 20ppm. Moreover, they are useful for allocating the right amount of time for clock drift whilst minimising the idle listening energy consumption. This can be done by tracking clock drifts to obtain their median and variation. Time duration and the corresponding energy consumption of idle listening within each slot can be conserved instead of applying the full of 20ppm.

B) Control slot length

Listening

There are two components of the listening period at the sources. Firstly, at the beginning of a control slot, the sources listen whilst the base stations calls the relevant commands such as the `fired()` and `send()` commands. These delays fluctuate and are non-deterministic. After the control packet reception, the sources are in listening mode again whilst the packet is delivered from the radio to the application layer. Reception delay, shown in Equation (5.10), includes the duration spent by the radio unit. Let a represent the summation of Equation (5.6), (5.7), (5.9) and (5.10). The listening period of sources is the difference between a and Equation (5.8).

Reception

As the reception and transmission periods should be equal, the reception duration is therefore represented by Equation (5.9).

Sleeping

The sources are switched to sleep mode after the control packet is completely received at the application layer. The sleeping duration is the difference between the proposed slot length and the wakeup duration which is the summation of the listening and reception intervals.

In summary, the proposed total control slot length is equal to the summation of Equation (5.6), (5.7), (5.9) and (5.10). Additional time is required for two-way propagation delay and clock drift. The two-way delay is very small compared to the sending and receiving delays and is non-deterministic. A 1-ms duration is reserved for the two-way propagation delay. For clock drift, the reserved duration is based upon experimental results.

C) Data slot length

Listening

Unlike control packet reception, the sources are switched to sleep mode after the whole packet is sent. The listening period is therefore equal to the summation of Equation (5.7) and (5.8).

Reception

The reception duration is required by the radio and it is equal to the transmission delay expressed in Equation (5.8).

Sleeping

Similar to the control slot, the sleeping duration is the difference between the proposed slot length and the wakeup duration which is the summation of the listening and reception intervals.

In this study, the receiving delay is included in the data slot to ensure that the whole packet is successfully delivered to the application layer. Therefore, the total data slot length is equal to the summation of Equation (5.6), (5.7), (5.9) and (5.10). As with the control slot, a 1-ms duration is reserved for the two-way propagation delay. For clock drift, the reserved duration is based upon experimental results.

5.5.6 Determination of guard length of frame

Equation (5.13) can be adopted to determine the guard length in the frame structure where clock drift is still one of the key aspects. Equation (5.14) demonstrates the guard length (g_f) of a frame.

$$g_f \geq (m-1)(n+1)(d)(20 * 10^{-6}) \tag{5.14}$$

The required frame guard length is therefore dependent upon the slot length excluding the guard length of slot (d), the number of slots (n) and the number of frames (m). The term ($n+1$) indicates that a frame consists of a control slot and n data slots.

Assuming that there are 2 frames and 100 and 1,000 slots are arranged for each frame, g_f should be slightly lower than $2d * 10^{-3}$ and $2d * 10^{-2}$ ms, respectively. However, a frame consisting of 1,000 slots is not feasible due to the limitation of the buffering capacity of the CC2420 radio. The base station sends a control packet when a new frame is started. A 1-ms gap is thus sufficient for the gap between frames. However, the duration between frames is mainly dependent upon the duty cycle required by an application. A longer duration is used for a lower duty cycle. The sources are in sleep mode during such a duration to save communication energy.

According to Equation (5.14), clock drift increases with frames. In some environmental applications such as Great Duck Island (GDI) [MSP+02], the sources are expected to operate for 9 months. In such a case, the clock drift would be very significant. Hence, in PoRAP, the base station broadcasts its control packet at the beginning of each frame in order to minimise the effects of clock drift. Therefore, Equation (5.14) can be reduced to Equation (5.15).

$$g_f \geq (n + 1)(d)(20 * 10^{-6}) \tag{5.15}$$

5.6 PoRAP Implementation

PoRAP is developed by using several components which are provided by TinyOS 2.x. For example, a command for transmission power adaptation is already included in the radio-related component. An additional interface for the control component is required for the radio start and stop. This section starts with demonstrating a PoRAP scenario which consists of two sources and a base station. The source is able to transmit only after it has received the control packet from the base station. Two communication phases, control and setup and then data delivery phases are described. Several states represent the operations of the source and base station. After control reception, the source enters the waiting state and becomes active again when its slot arrives. It then remains in the sleep state until the new communication cycle starts. PoRAP uses several components provided by the TinyOS. Several relationships between components are also addressed in this section. Finally, both control and data packet structures are described. Only two bits are used for each source for signaling the transmission power adaptation.

5.6.1 PoRAP scenario

PoRAP is developed to effectively support data communication in single-hop wireless sensor networks (WSNs). The base station communicates with its sources for controlling and data collection purposes. As the base station does not know when each source is booted, a setup process is required at the beginning of frame structure. Acting as a data receiver, the base station always listens to the medium for incoming messages after broadcasting the control packet. Hence, the base station desires extra power which can be obtained from external sources such as a desktop or laptop computer.

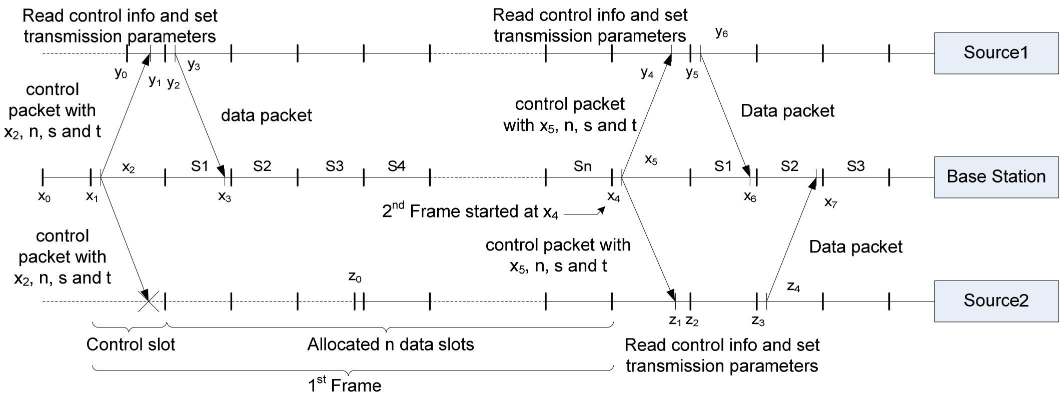


Figure 5.9: PoRAP scenario consisting of one base station and two sources

Figure 5.9 depicts the PoRAP scenario which consists of one base station and two sources. The following paragraphs illustrate two phases of PoRAP. The first phase, control and setup, is for broadcasting control information so that the sources can set their parameters to follow the defined schedule and transmission power adaptation notification from the base station. The data delivery phase is then established for the sources to transmit data packets to the base station. The control and setup phase is started again after the frame is completed to minimise the accumulation of clock drift.

A) Control and setup phase

Prior to data transmission, the sources have to setup their parameters based upon the control information received from their base station. The information such as number of slots, slot length and slot start time is used to control the sources in order to send data within an allocated slot at an adapted transmission power. Details of the power adaptation processes are illustrated later in this section.

As the base station has no information on when the sources join the network, it has to discover which sources are booted and ready for communication. In the control and setup phase, the base station periodically broadcasts control packets to all sources located in its communication range. The broadcasted packet is received by the booted sources and they use the received information to setup the communication parameters.

There are three main parts to the control information included in the control packet. The first attribute indicates the identification of the base station. This field supports a future enhancement of PoRAP which supports the multiple base station system. It can be also used to differentiate between the control and data packets. The second attribute is schedule related. Some information is required by the sources in order to synchronise with their base station. These parameters include the number of slots, slot length and the start time of the first slot. The base station specifies the slot start time with respect to the Start of Frame Delimiter (SFD) transmission in order to minimise the effects of application and hardware processing delays. The source assigned to the first data slot sets its timer to fire and sends data when the time arrives. Other sources start at different times and they compute the starting times from the slot information. According to Figure 5.9, a frame begins with a control slot followed by n data slots. In the first frame, the control slot starts at x_1 and the SFD of control packet is transmitted at x_2. The number of slots, slot length and slot start time are respectively denoted by n, s and t in Figure 5.9. This information is included in the control packet.

The transmission parameters are required to be completely set before the phase begins. Slot length determination for data slot can therefore be applied to the control slot. After successfully booting at y_0, Source1 receives the control packet at y_1. The control information is read by the source. The time of SFD reception is recognised and the first slot start time is set to t. The y_2 indicates when the first data slot is to start. Assuming that Slot1 (S1) is allocated for Source1, its data packet is transmitted and the SFD transmission is captured at y_3. Source2 is booted at z_0 whereas the data slots are not finished. Source2 has to wait until the slots are completed and the control packet for the next frame arrives. Source2 receives the packet at z_1. Assuming that Slot2 (S2) is allocated for Source2, it has to wait until S1 has completed and the SFD of its data packet is transmitted at z_4.

The base station periodically broadcasts its control packet. There are two main objectives of periodic broadcasting are maintaining synchronisation between nodes and supporting changes in network topology. Additional sources may be booted during the frame and some sources may be running out of energy. The number of sources is therefore modified by the base station.

B) Data delivery phase

Slots are allocated by the base station in order to facilitate data transmissions of the sources. The data delivery phase starts after the control packet is received by the sources. The number of slots is fixed as it assumes that the base station communicates with the fixed number of sources and the number is constant throughout the operation. Data collected by the sources is stored in the data packet and is delivered to the base station. PoRAP is a measurement-based protocol in terms of link quality monitoring and decides whether transmission power adaptation is required.

The Received Signal Strength Indicator (RSSI) is measured when the base station receives the data. The RSSI linearly relates to the transmission power and the RSSI-PRR relationship is established in Section 4.4.6. The PRR steeply increases with the RSSI up to a certain point. The increase in PRR then becomes insignificant or it becomes constant after this point. The RSSI is monitored and compared to the desired range. Power adaptation notification is conducted by the base station. The sources are notified by control packet reception in the next frame.

Apart from data, the identification (id) of a source is also included in the data packet. Specifying source id is an important issue and it may be done in several ways. For example, the SFD of the control packet reception time may be modified to obtain the id. However, sensors are considered resource constrained. Simple calculations should be included in the sources. Within the 128-byte buffering limitation in CC2420, one to two bytes should be enough to represent the id. Furthermore, the id can be assigned at installation time. Prior to deployment, a particular id is allocated to the source. For example, an id of 1 may be used for installing PoRAP in the first source in the network.

Additional power conservation is introduced during the data delivery phase. The strategy benefits from adopting the time-slot based concept. As sources know when to receive control and to transmit data packets, it is possible to periodically turn the radio on for such periods. Figure 5.10 describes the mode switching concept during the data delivery phase. The C&S, R, S and G represent control and setup, receive, send and guard, respectively.

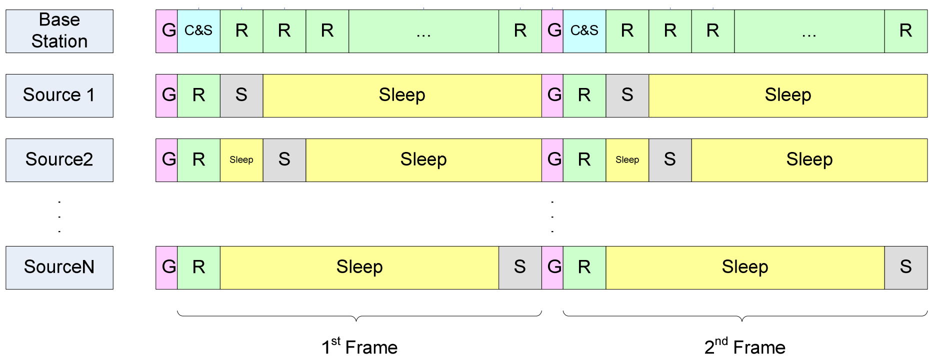


Figure 5.10: Mode switching during the data delivery phase

According to Figure 5.10, each source is in wakeup mode when its radio is turned on for two reasons; control packet reception and data packet transmission. Otherwise, its radio is turned off and the source is switched to sleep mode. However, the base station radio is always turned on. This strategy minimises idle listening power at the sources.

5.6.2 State diagram

This section aims to address several required states of the source and the base station. Sources and base station exchange some information in order to achieve the power conservation. Apart from describing the states, the calculations of several intervals such as waiting and sleeping are also given. The base station has to wait until all the sources have transmitted their data packets. There may be a case where some sources are booted during a data delivery phase. In this case, they have to listen until the current cycle is completed. If they have not received the control packet, they do not know when they can send their data. The next communication cycle is then started with a control packet broadcast. Several TinyOS components which are required for the implementation in each of the states are also described.

A) Source states

Figure 5.11 describes the state diagram of the source. In total six states are explained as follows:

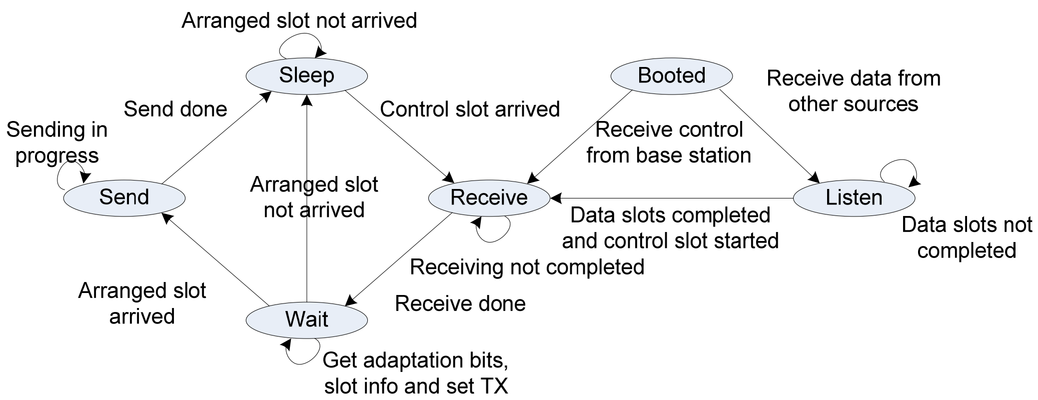


Figure 5.11: State diagram of source

Booted

This state is required for the sensors in order to enable them prior to their deployment. Several hardware components such as the radio are initialised via the use of the `SplitControl` interface which is provided by TinyOS. For example, `SplitControl` can be declared as `RadioControl` and it is used particularly for controlling the radio unit. The commands provided by `SplitControl` such as `start()` and `stop()` can be used to turn the radio on and off, respectively.

The sources are capable of sending and receiving after they are booted successfully. In PoRAP, the sources send only after they have received the control packet from base station. However, they may be booted during the ongoing data delivery. Several mechanisms on checking the source or type of packet are crucial. The sources enter a 'Listen' state if a data packet has been received. Otherwise, they receive the control packet and enter 'Receive' state.

Listen

This state is required only in the case when newly booted sources have joined the network and ongoing data delivery has not yet completed. Even if a slot has been allocated to each of them, they do not know when they can send as they have not received the control packet. They must not send and they have to be in a listen state. Otherwise, collisions at the base station are feasible as they and the owner of the current slot may transmit simultaneously. These sources have to wait until their control information has been received.

Once they have received a packet, the source of the packet is checked. In the current PoRAP development, the network consists of sources and a base station. The first field of the control packet stores the base station identification which is set to ‘0’. The identifications of the sources start with ‘1’. Thus, the listening sources can check where the received packet was transmitted from. The exit condition of this state is control packet reception and the sources enter ‘Receive’ state. Mode switching cannot apply in this state as the sources do not know when the frame is started.

Receive

The sources enter this state after they have received the control packet. All sources located within the communication range of the base station are in an active mode during this state. The `Receive` and `AMPacket` interfaces provided by the `AMReceiverC` component are required. In TinyOS, each message structure has a unique Active Message (AM) identification and it is required by `AMReceiverC` as a parameter. The `Receive` is a basic communication interface which provides some commands to obtain data payload length and it returns the pointer to the payload. Control information is therefore accessed and read for setting transmission parameters.

Another required interface, `AMPacket` is one of the AM interfaces. The AM layer is provided by TinyOS to multiplex access to the radio. The `AMPacket` provides basic accesses to the `message_t` abstract data type in TinyOS 2.x. Therefore, the data which is stored in the `message_t` such as node’s AM address and packet’s destination address can be set and obtained via `AMPacket`. The sources leave ‘Receive’ and enter ‘Wait’ state when the control packet reception is completed. When the control packet has been received by the application, the radio is switched off in order to minimise idle listening power.

After the control information is retrieved from its packet, the sources wait until their slots arrive. The waiting interval is calculated based upon the slot information in the control packet. Equation (5.16) demonstrates the wait interval calculation.

$$wait\ interval = ((me\ -1) * slot\_length) + slot\_start - (app\_rcv - sfd\_rcv) \tag{5.16}$$

Here the *me*, *slot_length* and *slot_start* indicate the source id, length of slot, time of starting first data slot. The *sfd_rcv* and *app_rcv* demonstrate the time of the SFD and the whole packet reception, respectively. The *slot_start* should be at least equal to the duration required by the sources to completely receive the control packet at their application layer.

Wait

Once the control packet has been received, the radio is stopped and the source is in this 'Wait' state. A timer is started to time the wait interval. The radio is started again for data transmission after the wait interval ends. The SFD reception time is used as a reference point for time synchronisation as two-way propagation delay is very small compared to the sending and receiving delays. Otherwise, synchronisation between source and base station may not happen due to the hardware-dependent and non-deterministic components within the sending delays.

Apart from scheduling information, the sources get the bits indicating the power adaptation notification. The `CC2420ActiveMessageC` component is required for adjusting the current transmission power. The component provides `CC2420Packet` interface and the `setPower()` command is called by specifying an integer argument which ranges from 1 to 31. The transmission power is set on a packet basis. Assuming that all parameters are set, the source enters the 'Send' state if its assigned slot arrives.

Send

The sources are in this state after their wait intervals have ended. They also set the destination address of their packets to the base station identification. The `AMSend` interface provided by `AMSenderC` component is required in this state. The destination AM address is taken by `send()` command which is provided by the `AMSend` interface. After the `sendDone()` event is signaled for sending completion, the sources enter the 'Sleep' state. The sleep interval is computed by using Equation (5.17).

$$\textit{sleep interval} = \quad \textit{NEXT\_BCAST} - [\textit{slot\_start} + (\textit{send\_done} - \textit{fired})] \tag{5.17}$$

Here the *NEXT_BCAST*, *send_done* and *fired* respectively indicate the duration of the next control packet broadcast, the time of packet transmission completion at the application layer and the time when the timer is fired. The *NEXT_BCAST* is defined in order to support the data reporting rate which is required by the application.

Sleep

The sources are switched to this state after the data packet has been successfully transmitted. Another timer is required to time the sleep interval. The radio is turned off during this interval. It will be started again for control packet reception after the sleep interval ends. The 'Sleep' state is established to minimise idle listening which is one of the major sources of wastage in the shared medium system. The sources leave this state to receive the control packet when the next frame or communication cycle is started.

B) Base station states

Figure 5.12 describes the state diagram of the source. In total five states are described as follows:

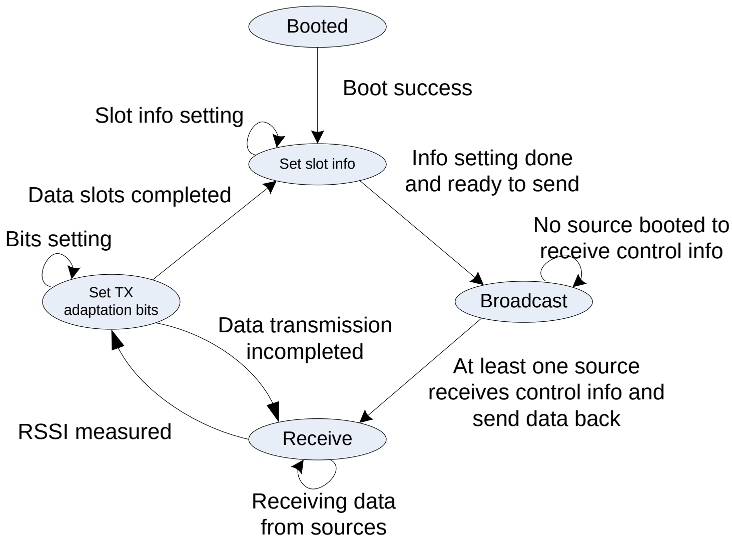


Figure 5.12: State diagram of the base station

Booted

The previous explanation for the sources applies to the base station. The base station has to be booted prior to operation. Several key interfaces such as Active Message (AM) and radio controls can be started in the 'Booted' state. In PoRAP, the base station is able to listen all the time as it has an extra source of power from the connecting computer.

Set Slot Information

This state is required before the control packets are transmitted. Three pieces of scheduling information including the number of slots, slot length and start time of the first data slot are set and the sources can use them to set their timing parameters. In PoRAP, the `Timer32khz` interface is used for timing. It generates 32,768 ticks per second. The width of the timing variables is 32 bits. Therefore, the slot length and start time requires 4-byte variables and fields in the control packet. After the settings are complete, the base station is ready to broadcast the control packet.

Broadcast

The control packet is broadcast to all sensors located within the communication range. The base station does not know when the sources are booted. A frame including one control and several data slots is broadcast. Some sources may be booted after the control packet has been broadcast. In this case, they have to wait until the next frame has started. The first booted source is identified as ‘1’. The broadcast address is specified when calling the `send()` command.

The measurements given in Section 4.5.2 indicate that the propagation delay is very small compared to the sending and receiving delays. Time synchronisation between nodes should therefore refer to data transmission and reception at the MAC layer. Equation (5.18) shows the calculation of the periodic transmission interval (*fire_in*) of the control packet.

$$fire\_in = NEXT\_BCAST + g_f \tag{5.18}$$

The g_f demonstrates the guard length of the frame and is required to accommodate the clock drift effects. Equation (5.19) demonstrates the calculation of g_f.

$$g_f \geq (NEXT\_BCAST + g_f)(20 * 10^{-6}) \tag{5.19}$$

The term $g_f\,(20 * 10^{-6})$ is minor compared to g_f. The above equation can be rearranged asin Equation (5.20).

$$g_f \geq (NEXT\_BCAST)(20 * 10^{-6}) \tag{5.20}$$

Clock drift is one of the major considerations. The base station’s and sources’ local clocks may be running at different speeds. These effects increase with the frame length. The sources may not receive the control packet which is sent in the next frames if the guard is not included in the frame. One possible reason is that the sources’ clocks are running at a slower rate compared to the base station’s clock. The sources may be sleeping when the control packet is sent.

Receive

The base station enters the ‘Receive’ state after broadcasting the control packet. The explanation for the sources can be applied here. The key operation within this state is the RSSI measurement during data reception. The `CC2420Packet` interface provided by `CC2420ActiveMessageC` component is required for determining the RSSI. The `getRssi()` command is called and returns a 32-bit signed integer. The base station leaves this state and enters the ‘Set TX Adaptation Bits’ state for setting the notification bits.

Set TX adaptation bits

After the RSSI measurements, the base station compares the observed RSSI to the upper and lower RSSI bounds which are obtained from the RSSI-PRR relationship. Several bytes are required for signaling the transmission power adaptation and the number of bytes is dependent upon the number of sources. As the maximum buffering capacity of the CC2420-based platform is limited to 128 bytes, only a few bits should be used for the signaling. In PoRAP, two bits are allocated for each source. Therefore, there are four possible notifications. Control and data packet structures are described in Section 5.6.4.

Once the bits are set, the base station returns to the ‘Receive’ state for the RSSI measurement. The exit condition is that the base station has received messages from all booted sources.

5.6.3 TinyOS component diagram

Some components required by PoRAP have been stated in the previous section. This section aims to describe the TinyOS components which are used in PoRAP. A brief introduction of TinyOS component is also given.

A) Overview of TinyOS components and notation

TinyOS is an operating system which is specifically developed for embedded systems such as wireless sensor networks (WSNs). It is written by the nesC programming language which is a C dialect. TinyOS also provides a programming environment so that new protocols or applications can be developed by adopting and modifying several existing components. The protocol consists of several components which are assembled or wired together. In each component, the names of interfaces along with their implementations are defined.

A nesC component provides and uses an interface. Provided interfaces represent the functionalities of the component and they can be used by the other components. Interfaces are bidirectional. They specify a set of commands which are implemented by those components which provide them. Interfaces also specify a set of events which are implemented by those components which use them. If a component requires to call a command in an interface, this component has to implement the events of that interface. A component may provide or use multiple interfaces or the instances of the same interface.

There are two types of components in nesC which include modules and configurations. Implementations of interfaces are described in the modules. Configurations are used to assemble the components together by means of wiring, which is the mechanism of connecting the interfaces used by a component to the interfaces provided by other components. Every nesC application is described by a top-level configuration where all wirings between the components are included.

Standard notations are provided by the TinyOS community. A single box represents a self-developed module. In PoRAP, `SourceC` and `BaseP` are respectively modules of the source and base station. One of the key interfaces used by the source is `CC2420Packet` which provides transmission power adaptation. The same interface is also used by the base station for RSSI measurement. A double box represents the configuration, or component, which is generally required by all nesC applications. For example, the `MainC` is always required as it enables boot processes. A double box with dashed border line indicates that the component is generic. For example, the sources require two instances of a timer component for timing the waiting and sleeping intervals. Wiring between components is indicated by a line with arrow. The arrow head is pointing to the component which provides the interfaces.

B) Structure of source's components

The structure of a source's components is depicted in Figure 5.13.

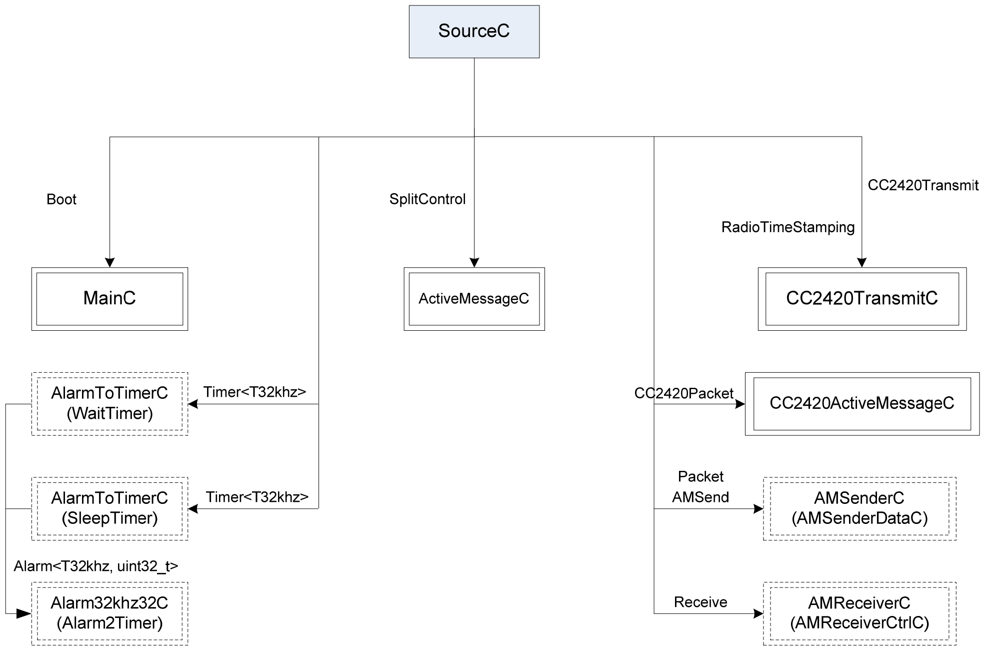


Figure 5.13: TinyOS component diagram for a source

According to Figure 5.13, the source module is represented by `SourceC`. It uses several interfaces provided from eight components. The interactions between `SourceC` and these components are represented by wiring processes which are described as followed:

1. `MainC`: This component is general and is required in all modules. It provides the `Boot` interface which is used for booting the module for operation.

2. `ActiveMessageC`: The message structure in TinyOS 2.x is named "Active Message". This structure is general so that the sensors can understand each other. This component provides a key interface called "`SplitControl`" which is useful for starting and

stopping the hardware such as the radio. In PoRAP, an instance, `RadioControl`, can be created to control the CC2420 radio. To start and stop the radio, the `start()` and `stop()` commands can be used by respectively calling `RadioControl.start()` and `RadioControl.stop()`.

3. `CC2420TransmitC`: Two important interfaces are provided by this interface. The `CC2420Transmit` enables the modification to the payload especially when the SFD of the packet is transmitted. This feature is crucial when the content is not known until the message has been forwarded to the MAC layer. The other interface is `RadioTimeStamping` which is used for obtaining the specific time of data transmission and reception at the MAC layer. This is important in the schedule-based protocol as time synchronisation refers to those timestamps at the MAC layer.

4. `CC2420ActiveMessageC`: This component is important to PoRAP as it provides the `CC2420Packet` interface which enables the transmission power setting by calling `CC2420Packet.setPower(&data_message, power)`. The `setPower()` command accepts two arguments; the address of the data message and the required power level. Moreover, the current transmission power level can be obtained by calling the `CC2420Packet.getpower(&data_message)`.

5. `AMSenderC`: This component is generic and an instance called "`AMSenderDataC`" is created to facilitate data transmission. Two important interfaces are used by `SourceC`. Firstly, the `Packet` interface is used for obtaining the payload part from the whole packet. This is useful for modifying the content in the payload without unintentionally accessing or amending the header and footer parts of the packet. Secondly, the `AMSend` is required for message sending by calling the `AMSend.send()`. The source can check if the packet is already transmitted and some processes can be initiated by signaling the `AMSend.sendDone()` event. For example, the radio is stopped after the whole packet is sent.

6. `AMReceiverC`: Like `AMSenderC`, this component is generic. Its instance, `AMReceiverCtrlC`, is created to facilitate data reception in PoRAP. The `Receive` interface is used and several processes are performed when the `Receive.receive()` is signaled. Firstly, the `Packet` interface is used to extract the control payload as the source has to synchronise with the base station and adjust its current transmission power. After the whole control packet has been received, the radio is stopped.

7. `Alarm32khz32C`: is used for timing the waiting and sleeping intervals. Its commands take and return an unsigned 32-bit integer. Two alarm components are thus required. The returned values from the Alarm component must be used for calculating waiting and sleeping intervals. The 32-bit Alarm must be converted to Timer for such calculations. Another component, `AlarmToTimerC`, is required.

8. `AlarmToTimerC`: Two instances of this component, `WaitTimer` and `SleepTimer`, are created for the source. They are respectively used for timing the waiting and sleeping intervals. The `MoteWaitTimer` is an interface of the `WaitTimer` and the `MoteSleepTimer` is an interface of `SleepTimer`. The `WaitTimer` interface is started by calling `MoteWaitTimer.fired()` command. It is called after the source has received the control packet whereas the `SleepTimer` is called after the data packet has been sent.

C) Structure of the base station's components

The structure of the source's components is depicted in Figure 5.14. The base station module, `BaseP`, can be considered as an enhancement of the BaseStation application in the TinyOS 2.x. The BaseStation is a basic TinyOS utility application. It acts as a bridge between the serial port and the radio network. It is developed to forward the data received by the radio to the serial port and then show it on the computer screen. Additional work has been conducted to manage the buffer of the radio unit.

Several enhancements are made to the BaseStation as follows:

- The base station can broadcast its control packet to the fixed set of sources which are located within its communication range.

- The base station is able to measure the Received Signal Strength Indicator (RSSI) during data reception.

- The base station compares the observed RSSI to the bounds and sets the notification bits in order to signal the transmission power adaptation to the source.

- The base station is able to schedule the control packet broadcast to maintain time synchronisation between itself and the sources.

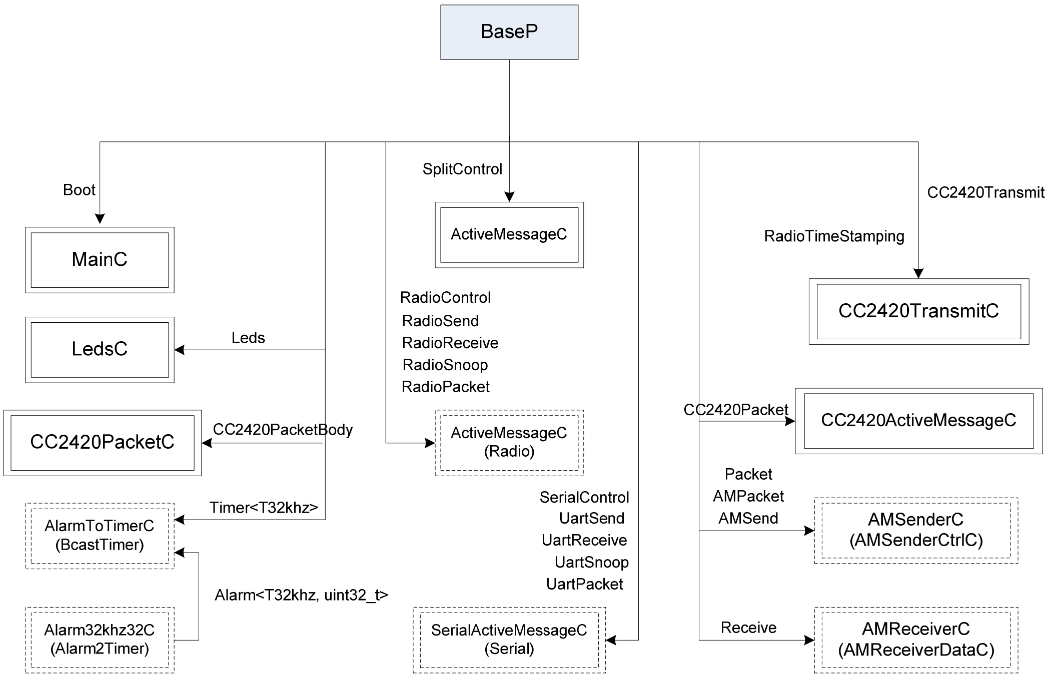


Figure 5.14: TinyOS component diagram for the base station

According to Figure 5.14, more components are required by the base station compared to Figure 5.13. The main reason is that some components including `LedsC` and `Radio` as an instance of the `ActiveMessageC` and `SerialActiveMessageC` are already included in the BaseStation. The `Leds` is used for debugging the application operation. The `Radio` is required for controlling the radio especially when it has to communicate with the serial port. The received data is forwarded from the radio to the serial port via uart. The `SerialActiveMessageC` is used for controlling the uart.

In order to achieve the enhancements stated previously, additional components are required except for the notification bit settings as follows:

1. `AMSenderC`: An instance of this component called "`AMSenderCtrlC`" is created to facilitate control packet transmission. Two important interfaces are used by `BaseP`. Firstly, the `Packet` interface is used for obtaining the payload part from the control packet for message modifications. Secondly, the `AMSend` is required for message sending by calling the `AMSend.send()`. Note that the `AMPacket` is currently used by the traditional BaseStation application.

2. `CC2420ActiveMessageC`: This component is important to PoRAP as it provides the `CC2420Packet` interface which enables RSSI measurement by calling `CC2420Packet.getRssi(msg)`. The `getRssi()` command accepts an argument

which is the message being received. Note that the transmission power can be set by this interface. In PoRAP, the base station always initially broadcasts its packet at the maximum power level.

3. `Alarm32khz32C`: is used for timing the control packet broadcast. An alarm component is thus required. The explanations given in the previous part for the source apply to the base station.

4. `AlarmToTimerC`: An instance of this component, `BcastTimer`, is created for the base station. The `fired()` command is called after the control packet is sent.

In summary, several TinyOS components are used in PoRAP. The main components are those which provide transmission power setting, RSSI measurements, scheduling, modification to payload, sending and transmitting. Several instances can be created from a generic component such as an alarm or timer. The source radio is started and stopped by two instances of the `SplitControl` interface. The base station module is an enhancement of the existing BaseStation utility application in TinyOS 2.x. The main enhancements include data transmission, RSSI measurements and scheduling.

5.6.4 Control and data packet structures

Two packet formats are required in PoRAP. The control packet is used in the control and setup phase. It contains essential information for transmission power adaptation and time synchronisation. The data packet is used to deliver the sensed phenomenon to the base station. Details of both packet structures are given in this section.

A) Control packet

The control packet structure is shown in Figure 5.15.

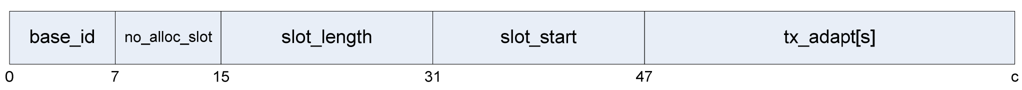


Figure 5.15: Control packet structure

The control packet consists of 5 fields. The first byte, `base_id`, represents the base station's address. The address can be assigned at installation time. The `no_alloc_slot` demonstrates the number of allocated slots and is stored in an 8-bit field. Slot length is contained in the 16-bit `slot_length`. The time when the first data slot is started is demonstrated in the 16-bit slot_start. Finally, the tx_adapt[s] is used to notify the sources whether transmission power adaptation is required.

The default payload size in the message_t abstract data structure is set to 28 bytes. Declaration of a larger payload size in the Makefile is required for larger payload. However, the maximum payload for the CC2420 is approximately 117 bytes. According to Figure 5.15, the former fields take 6 bytes. The size of tx_adapt[s] depends upon the number of sources which are capable of communicating with the base station directly. Therefore, *c* in Figure 5.16 is equal to (47 + [((s – 1) / 4) + 1] * 8) where *s* represents the number of sources. The "/" is the division operator where the remainder is discarded. The structure of tx_adapt[s] is given in Figure 5.16.

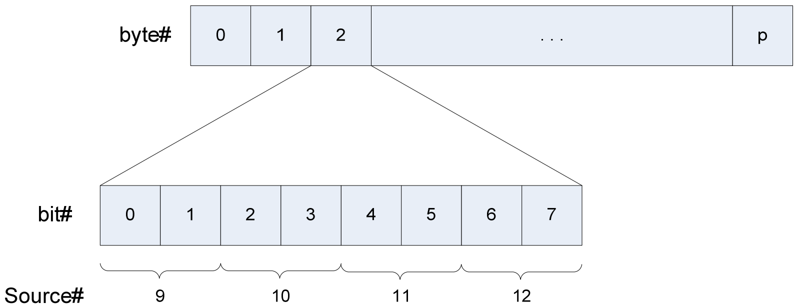


Figure 5.16: Structure of tx_adapt[s]

where *p* indicates the number of allocated bytes. According to Figure 5.16, two bits are arranged for a source and therefore one byte supports four sources. There are four possible patterns of two bits for the notification of transmission power adaptation and three of these are summarised in Table 5.2.

Table 5.2: Three possible patterns for transmission power (TX) adaptation

Pattern	Meaning
00	RSSI is in the range, keep TX the same
01	RSSI is higher than required, decrease TX power
10	RSSI is lower than required, increase TX power

The comparison of the RSSI measures is the key to transmission power adaptation. For example, an increase in TX is requested if the observed RSSI is lower than required. The power is retained if the measured RSSI is in the desired RSSI range. The base station sets these particular bits to '00'. The data packet structure is illustrated in the next section.

B) Data packet

The sources transmit their data packets to the base station within assigned data slots. The data packet structure is shown in Figure 5.17.

Figure 5.17: Data packet structure

The data packet consists of 2 fields. The 8-bit `source_id` field represents the sensor address which is defined at the installation time. Finally, the data is stored in `data[q]` where *q* is the number of bytes used for storing data. The width of `data` field is defined by the application. Therefore, *d* can be represented by (47 + (8 * *q*)).

5.7 Conclusion

This chapter has described PoRAP design and implementation. Several functional requirements are outlined in order to address which components are required. PoRAP adopts the measurement-based approach to determine the current link quality by means of RSSI and the schedule-based approach to access and employ the shared wireless medium. The transmission power is adapted based upon the current link quality. A lower power can be used while the data loss is minimised. Major sources of energy wastage such as collision can be avoided and the idle listening can be also minimised.

In PoRAP, a fixed set of sources is determined and they are controlled by their base station. Several models used for estimating sending and receiving delays together with a guard length are proposed. These models are proposed by looking at the experimental results obtained in Chapter 4. A frame is used to represent communication in PoRAP and consists of one control slot followed by data slots. The base station broadcasts a control packet within the control slot. The duration of the next control packet broadcast can be computed by looking at the included scheduling information in the control packet. The sources thus know when they should restart their radios.

PoRAP consists of two main components including a base station and sources which operate together in order to collect the physical data from the phenomenon. The application always specifies its requirement in terms of reliability in which minimization of data loss is often required. PoRAP is implemented by using TinyOS 2.0.2. Some existing components provided by TinyOS can be modified to achieve the goals. For example, the radio-related components have some interfaces and commands which make RSSI measurement and transmission power adaptation feasible. Alarm and Timer components can be used for scheduling the communication. A timer instance is used by the source for timing the waiting interval. It is started after the control packet is received. Another instance is started after the data is sent. The base station module is an enhancement of the existing BaseStation utility application in TinyOS. The enhancements include control transmission, RSSI measurement, notification bit settings and packet broadcast scheduling.

Two packet structures are used in PoRAP. The control packet is always broadcast by the base station at the maximum power level. After data reception, the base station compares the observed RSSI to the bounds and determines the power level to signal the source. Only two bits are used for signaling to each source the amendment to the current power level. Scheduling information is also included in the control packet. After the control packet is received by the source, the payload is read and the source sets its scheduling parameters and adjusts the power for the next communication cycle. The next frame begins after all sources complete their transmissions.

Chapter 6

PoRAP Energy Conservation Evaluation

This chapter describes PoRAP evaluation and the experiment set up to evaluate the energy conservation of the protocol. The work addresses four subjects;

- **Range Feasibility**: The distance over which direct communication is possible is analysed.

- **Direct Communication**: An analysis of the measurements in the previous chapter and associated literature demonstrates the viability of direct communication. A comparison of the energy consumption for direct and multi-hop communication is made. The effects of distance between nodes and densities are studied. A densely populated network benefits from direct communication as no message forwarding is required.

- **Adaptive transmission power**: An evaluation of the feasibility and benefit of adaptive power transmission is performed to discover the optimal region where transmission energy is conserved and a reliability of nearly 100% is maintained.

- **Scheduling**: An evaluation of clock drift is performed. Clock drift is important in the schedule-based approach. It is hardware-dependent and also depends upon the duration between two consecutive transmissions. By knowing the median and the variation of clock drifts, the sources can adjust their schedule and idle listening energy can be conserved.

PoRAP is specifically developed for the single-hop wireless sensor networks where the sources directly communicate with their base station. Communication range of sensor is thus important to make the single-hop communication possible. One of the main objectives is to address the scenario where the single-hop can be used and it is more energy efficient than the multi-hop.

Transceiver is one of the main hardware components of the sensor which make data communication feasible. Recent transceivers such as CC2420 support programmable transmission power. Lower power level can be used instead of always transmitting at the maximum whilst the reliability of nearly 100% is maintained. The optimal region where energy conservation and reliability are achieved depends upon environmental factors. PoRAP adopts the measurement-based approach which the Received Signal Strength Indicator (RSSI) is measured at the base station and power adaptation is signaled to the sources.

In order to avoid the sources of energy wastage such as collision and idle listening, PoRAP adopts the schedule-based scheme. A time slot is allocated for each source and it can be used for data transmission. Time synchronisation is required and clock drift is important. Greater clock drift results in longer duration in the listen state or unavailability of time synchronisation. More listening energy is thus consumed or a significant amount of energy is wasted on unsuccessful data delivery. Monitoring the clock drift is useful to reduce the idle listening whilst time synchronisation is maintained.

6.1 Overview

PoRAP is designed for the scenario where direct communication between sensors and a base station is possible and where it is important to conserve their power reserves without compromising reliability. Direct communication eliminates the need for sensors to receive and forward data from other sensors. It makes it simpler for dynamic transmission power adaptation to be used to reduce consumption whilst preserving reliability and it makes it easier for the base station to schedule sensor transmissions. The spread of the Internet and the widespread distribution of power supplies mean that for many locations it will be possible to build sensor networks where direct communication with a base station is possible. Further, multiple base stations, and by extension the sensors which communicate with their base station, may be connected to a sink by means of standard Internet protocols. In this way sensor networks may be built that cover a wide geographic area and function around direct communication between a sensor and its base stations.

As energy awareness is the main design objective of PoRAP, this evaluation focuses on energy consumption. The chapter presents analysis, simulation and experimentation which have been used to evaluate PoRAP. The key question addressed is how effective PoRAP is at preserving energy. The protocol is validated to demonstrate that the implementation works and the parameter space within which the protocol is effectively quantified. The effects the main protocol features, of direct communication, transmission power adaptation and transmission scheduling have on energy conservation are each quantified.

The first part of the chapter is split into four sections addressing the four parts of the evaluation; the feasible communication range of the sensors, the communication, the adaptive power transmission and the scheduling of the transmission. This section then outlines the parameters of the equipment and their physical limitations before addressing any comparison of techniques.

The second part of the chapter describes a comparative study which focuses on transmitting current consumption. In the multi-hop system, the intermediary nodes between the source and the base station must ensure data transmission and a lower power can be used for communication.

However, higher power is required in the single-hop as the sources send data directly to the base station. The power setting required for each distance is obtained by considering the relationship between the RSSI and distance as discussed in the previous chapter. The distances between sources and the density of nodes are varied in this study allowing the total and per source current consumption to be computed. This section therefore allows an estimate of power conservation using intelligent monitoring of measurements.

Determination of the feasible communication range of sensors: One of the main hardware components of a sensor is its transceiver which allows the sensor to communicate with the other nodes. Communication is via radio and the waves propagate in all directions. The sensors located within a transmitter's range can thus hear the signal and initiate communication.

Communication range is important in direct communication as the source transmits directly to the base station. Strength is inversely related to the distance and perfect conditions without obstacles and good weather are assumed in the free space propagation model used. Statistical analysis is conducted to discover the feasible indoor and outdoor ranges with the motes used.

Direct communication and multi-hop networks: A combination of analytical and measurement studies are used to establish the scenarios within which direct communication between a sensor and its base station is possible. These scenarios are then investigated to compare the power demands of multi-hop and direct communication, both for the sensor network as a whole, for regions within the network and for individual nodes.

In the first instance it is the transmission range of a sensor that limits the applicability of a single hop network. If it is not possible for a sensor to transmit to the base station directly then multi-hop communication must be used. The transmission ranges of the sensors used in these experiments are specified in [CC2420].

It is possible to use multiple base stations to extend the range of a network based on direct communication, beyond the physical reach of a single node's transmission range. However, if nodes are thinly distributed the ratio of nodes to base stations will be low and such an extension is not economical. Consequently, the density of nodes distributed across the area is important in determining whether a multi-hop or direct communication approach is appropriate.

Building sensor networks, which use direct communication between a sensor and its base station, eliminates some energy-conservation related concerns. Multi-hops imply multiple transmissions and receptions required to forward the data to its destination [SMW08]. A sensor needs to spend energy not just on transmitting its own data but also on receiving and transmitting the data from other sensors. This phenomenon has the greatest effect on nodes that are located near the base station. Messages are forwarded through them to the base station [Hae03, Hae04], and consequently they will run out of power before the edge nodes. However, when direct communication is used, the data may have to be sent over a larger distance and therefore each individual hop may require more power.

In order to evaluate the feasibility of direct communication, measurements of the relationship between transmission power, reception signal strength and distance of transmission are used. These are then utilised as inputs to the comparative studies of the power required for communication on direct communication and multi-hop networks with the same topology.

Adaptive power transmission: There is a trade off between power consumption and reliability. The greater the transmission power used, the stronger the received signal and therefore the greater the reliability of data transfer. In order to test whether the power is correctly adapted, two experiments were conducted. These quantify the extent to which PoRAP is able to save energy without compromising reliability.

The Packet Reception Rate (PRR) is important as a measurement of reliability. A low PRR implies either wasted energy, through data being retransmitted or data being lost, neither of which are desirable. The Received Signal Strength Indicator (RSSI) is a convenient measure of the received signal strength. As shown in Chapter 4 and in [LZZ+06] and [SDTL06] there is a strong correlation between the value of RSSI and PRR. PoRAP works by the base station monitoring the RSSI for each sensor. If it strays outside of an upper or lower bound the sensor is told to lower or increase its transmission power. The goal is for each sensor to use the minimum power required for a high PRR.

An implementation of a sensor network was deployed and experiments were conducted into adaptive power conservation demonstrating that significant amounts of energy can be saved without impacting onto the reliability of the packet reception rate.

Scheduled reporting: In direct communication, the operations of sources such as data communication can be controlled by the base station. All nodes share the medium and access can be scheduled. The source's radio is started for control reception and data transmission only. The length of the time slot is important in the schedule based system.

PoRAP adopts a schedule-based approach where a slot is allocated to each source. Sources' transmissions are scheduled in order to avoid collisions and minimise idle listening. A frame is used to represent a communication cycle. The frame begins with a control slot, which is followed by a data slot for each sensor and concludes with a silent period. The first data slot is started after the control packet is completely received and sensors can calculate their schedule relative to the start of the control packet. During the silent period neither sensors nor the base station communicate and the silent period is terminated by the next control frame.

In order for synchronisation between sensors and their base station to be maintained the clock drift needs to be taken into account. Clock drift is important in this schedule-based approach as the greater the drift between clocks the more time sensors need to spend in an idle listen state in order to be sure that they receive the start of the control packet correctly. Also collisions may occur and a significant amount of energy is wasted on unsuccessful data delivery. By measuring the clock drift between two motes, their time can be synchronised and switching on and off can be done efficiently without loss of energy. The benefit of schedule versus contention based reporting is discussed as part of the evaluation.

Clock drift occurs as nodes' local clocks may be running at different speeds. The size of clock drift is hardware-dependent and therefore varies from sensor to sensor. The longer the gap between two transmissions the greater the clock drift between sender and receiver. The data sheet for CMR200T, which is used by the Tmote sensor platform [Lim06], specifies that clock drift will be up to 20 parts per million (ppm) [CMR200]. However, by measuring clock drift it is possible to then predict drift and therefore reduce the idle listening required for accurate synchronisation between a sensor and its base station.

In PoRAP each node tracks its clock's drift from the base station. Consequently, sensors can accurately estimate when to switch on their receiver for the arrival of the next control packet. However, there is variation of clock drift which limits the accuracy with which synchronisation can be achieved and requires sensors to engage in idle listening. The measurement and variation of clock drift is included in the evaluation to reduce the amount of idle listening PoRAP requires to correctly receive control packets. This in turns allows the energy efficiency PoRAP's scheduling system to be evaluated.

6.2 Methodology

This section aims to describe several methodologies which are used to explore the possible communication ranges of sensors, demonstrate the benefits of single-hop when it is applicable, discover the optimal region obtained from adaptive transmission power and address the characteristics of clock drifts and how they relate to the energy conservation.

6.2.1 Feasible communication ranges

There are two main parts in this chapter. The first part addresses the feasibility of single-hop deployment and the efficiency of PoRAP in terms of energy conservation. In order to determine the possible communication ranges, estimation on received signal strength and the minimum

Received Signal Strength Indicator (RSSI) which is reported by the receiver's transceiver are used. The selected sensor platform in this dissertation is Tmote and it employs the CC2420 radio which operates at the frequency range of 2.4GHz. Signal propagation at such range requires line-of-sight (LOS) [Cla01]. The free space propagation model is used to predict the received signal strength at various transmission power settings and distances. The RSSI of -95dBm is used to consider the feasible communication range as the CC2420 does not report the observed RSSI below than -95dBm. Therefore, the feasible ranges are obtained from the interceptions between the -95dBm horizontal line and the curve between distance and reception strength.

Apart from using the free space propagation model which is based upon a perfect condition, the feasible ranges are also obtained from the experimental results in literature review [SKPP07] and Chapter 4. The indoor measurements of RSSI at various distances in Chapter 4 are plotted to discover the feasible ranges. As eight power settings were used in the experiment, a statistical analysis is required to estimate the ranges at all possible settings. The experiment in [SKPP07] was conducted outdoor. Similar procedures are applied to obtain the feasible outdoor ranges.

6.2.2 Direct communication and multi-hop networks

Several benefits are observed when direct communications between the sources and the base station are feasible. The source does not receive and transmit the packets from its neighbours to forward them to the destination. A significant amount of energy can be conserved. Three analyses are conducted where the energy requirements are compared. A line topology is used. Message forwarding is required in the multi-hop and the minimum power is used in the hop-by-hop communication.

In the first analysis, a node is placed in each region which corresponds to a specific transmission power level setting. There are eight regions with respect to eight different setting in [CC2420]. Each node therefore communicates directly with the base station. Transmitting and receiving current consumption is calculated based upon the Tmote data sheet [Tmote].

Five nodes are uniformly scattered over a line topology in the second analysis. The distance between nodes is varied between one and ten metres. The measurements of power settings obtained in Chapter 4 are used where Tmote Invent and Tmote Sky were used as source and base station, respectively. The base station remained at the same location whilst three sources were placed at ten different locations. An average of power settings for 50 packet transmissions was calculated. The maximum of 50-m distance is obtained if each node is placed 10m away from its neigbours. According to [CC2420], the maximum power setting can be used for the direct communication.

The third analysis examines the effect of varying the density of node distribution. Nodes are uniformly scattered a line topology which spans a distance of 50m. Seven different numbers of nodes are set to 1, 2, 5, 10, 20, 50 and 100. The required transmission power setting is also obtained from the measurements in Chapter 4.

6.2.3 Adaptive power transmission

There are two experiments in this study. The first focuses on testing whether PoRAP correctly adjusts the transmission power and investigates the transmission power required for each cycle. In total 20 Tmote Sky sources were placed at 20 separate locations with 14 different distances to address the effects of location. A Tmote Sky base station broadcasts the control packet at the maximum power at the start of each communication cycle. Each source is allocated to a time slot when it can send. After the control packet has been received, a source transmits its data at the maximum power. Upon data packet reception, the base station measures the RSSI and compares it against the RSSI minimum and maximum settings. The adaptation signal is a 2-bit setting included in the control packet signaling to the source to adjust its power accordingly. The source should correctly adjust its power corresponding to the notification generated by the base station. Further, the PRR is also computed to determine the reliability. The communication proceeds for 1,000 cycles.

The second experiment investigates the effects of different RSSI settings for PRR and energy consumption. Sensors are power and resource constrained so data transmission at the maximum power level may provide the required reliability but no conservation of energy can be achieved. However, a lower power may be used but the required reliability may not be met. The main objective of the second experiment is to discover the optimal point at which both energy conservation and reliability can be obtained.

Transmission power relates to RSSI and the RSSI relates to the PRR. In order to determine the optimal region where energy conservation is achieved without harming the reliability, several RSSI settings are analysed. The PRR for each setting is computed to see the effects of the settings. The optimal region is the one which maintains the PRR as near to 100% as possible. The current consumption for each source for different RSSI settings and distances is also calculated to quantify the energy conservation.

The same set of sources and base station can be used for both experiments. All nodes remain at the same location throughout the study. In order to maximise the control packet reception, the base station broadcasts at the maximum power as do the sources for their first data transmissions. A specific RSSI setting is used for the first experiment is required to test the validity of power adaptation. The setting consists of the minimum and maximum RSSI values. The main reason of specifying the setting as a range is to prevent packet loss and reduce energy consumption. The power may be continually decreased unless the minimum RSSI is set when packet loss may occur. No transmission energy will be saved if the maximum RSSI is set.

6.2.4 Scheduling

A sensor has an oscillator which generates timing signals or ticks. The number of ticks generated in 1 second depends upon the timer interface provided in TinyOS. In this study, a 32KHz clock is selected and it provides 32,768 ticks per second. Clock drift occurs as a result of uncertainty in the ticking rate. Different local clocks may run at different speeds. Clock drift may be accumulated and time synchronisation is no longer maintained. Clock drift is crucial in a schedule-based system like PoRAP. The control packet is broadcast at the beginning of each frame or communication cycle to decrease the effects of clock drift.

This analysis aims to conduct clock drift measurements and discover their relationship with the energy conservation by means of further minimising idle listening. In total 20 Tmote Sky sources were used and they transmitted data to the base station every 5 minutes with respect to the Great Duck Island scenario [MPS+02]. The base station measured the clock drifts and a statistical analysis was conducted. The results were compared to the 20 parts per million (ppm) which is recommended in [CMR200]. Further, the durations between two consecutive transmissions were varied between 5 minutes and 1 day to determine the effects. Additional statistical analyses are conducted to demonstrate the effect of different durations between two consecutive transmissions. Calculations of medians and variations in the drift measurements are also compared to the 20ppm. The source can be in sleep mode longer if the width of variations is less than 20ppm.

6.3 Determination of the feasible communication range of sensors

The transceiver in a sensor allows the sensor to communicate with the other nodes. The sensors located within the transmitter's range can hear the radio signal and initiate the communications. The Tmote sensor platform used in this dissertation employs the CC2420 radio which operates at the frequency range of 2.4GHz. According to [Cla01], the radio wave propagation of the 2.4GHz transceiver requires line-of-sight (LOS).

The communication range is important in direct communication scenarios as the source transmits directly to the base station. The free space propagation model is widely used to predict the reception signal strength and the strength is inversely related to the distance. Perfect conditions without obstacles and with good weather are assumed in the model. Statistical analysis should be conducted on the measurements to discover feasible indoor and outdoor ranges.

6.3.1 The free space propagation model

This model is used to predict the received signal strength when an unobstructed line-of-sight path exists between the sender and receiver [Rap96]. The degradation of signal strength varies with the square of the sender-receiver distance (d^2). An equation for predicting the expected received signal level (RSL) is provided by [Cla01] and is shown in Equation (6.1).

$$RSL \;=\; P_t + G_t + G_r - 92.44 - 20\log f - 20\log d \tag{6.1}$$

where P_t is transmission power (dBm), G_t and G_r are transmit and receive attenna gains (dBi), f is frequency (GHz) and d is the distance between the sender and receiver (km). RSL uses the same unit as that of P_t.

Figure 6.1 demonstrates feasible communication ranges of a sensor using the CC2420 transceiver set at various transmission power levels and distances. As the CC2420 does not report the observed RSSI below -95dBm, the last distance which provides measurable RSSI is determined as the maximum range. Transmission power levels specified in [CC2420] are used for P_t and they include 0, -1, -3, -5, -7, -10, -15 and -25dBm. Tmote Sky employs an inverted-F and monopole antenna. There are several studies which focus on the analysis and design of an inverted-F antenna such as [SKTM02], [BH09] and [WCSC10]. Each of them recommends different values of the transmit and receive gains. According to [WCSC10], the G_t and G_r are 3.1dBi. The value is chosen as the corresponding return and is close to that specified in [Tmote]. The frequency is 2.4GHz.

Figure 6.1 shows the RSSI computed from Equation (6.1) at the eight different transmission power settings given in [CC2420 and Tmote] and at various distances.

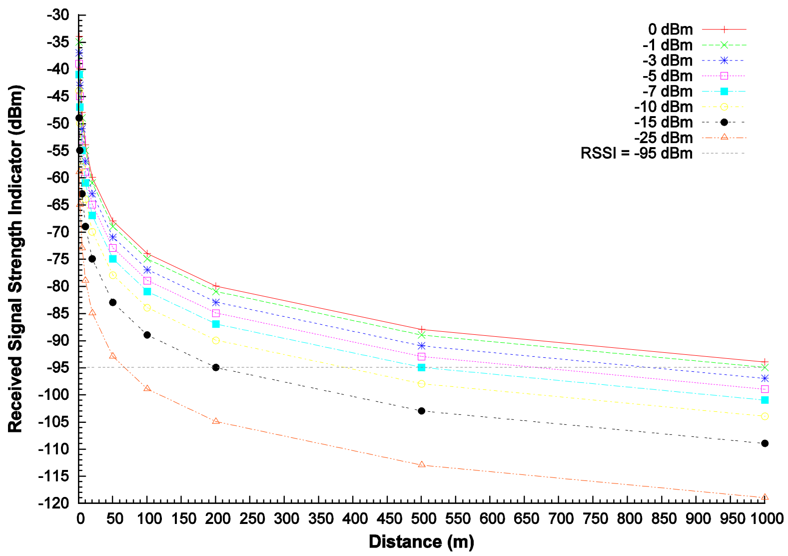


Figure 6.1: Theoretical RSSI at various distances and power settings

The selected eight power settings are the same as those in the data sheets of the Tmote sensor platform [Tmote] and its transceiver [CC2420]. According to the results, a lower transmission power provides lower RSSI at any distance. Reduction in the RSSI is greater at the distances lower than approximately 100m. The results demonstrate a significant range for direct communication in wireless sensor networks. The feasible ranges based upon -95 dBm are 65, 200, 390, 500, 650, 870, 1,000 and longer than 1,000m for the transmission power settings of -25, -15, -10, -7, -5, -3, -1 and 0 dBm, respectively.

However, there are two main assumptions which, under some circumstances, may make the results impractical in a real production. A clear line-of-sight and good weather are assumed in Equation (6.1). The theoretical range cannot be achieved in the presence of physical or temporal barriers such as plants and humans. Moreover, weather changes are likely at any time during the operation. Several barriers along with some recommended empirical formula are given in [Cla01]. The calculations of path losses in dB/km (decibel per kilometre) due to precipitation, signal absorption and ground coverage are also provided. The recommended models mainly focus on systems which have communication ranges up to many kilometres and operating frequencies up to hundred or thousand giga-hertz. Sensors have 50m indoor and 125m outdoor ranges. Instead of using the path loss estimation models, experimental measurements should therefore be used to analyse the sufficiency of the prediction model and estimate feasible communication ranges.

6.3.2 Estimation of communication range

Using results based on the experimental studies on location as a determination of necessary transmission power, provided in Section 4.4.3 in Chapter 4 and in [SKPP07], models for predicting the communication ranges by non-linear regression analysis were developed for indoor and outdoor environments.

For an indoor environment, the measurements in Figure 4.2 (b) are used. In total 10 different distances, 1, 2, 3, 4, 5, 7, 10, 13, 16 and 20m, were used to measure the RSSI at the receiver. The experiment was repeated 50 times for each transmission power setting. The average RSSI was computed and plotted against the distance. Linear, logarithmic and inverse methods of curve estimation were applied to the scatter plots. The logarithmic approach provided the highest R-square value which describes how well a regression line estimates the set of real data. An R-square value of 1 means that the regression line provides a perfect fit. The R-square values of over 0.85 were obtained. Figure 6.2 shows the logarithmic curve estimation of the measured RSSI based upon the indoor environment experiment.

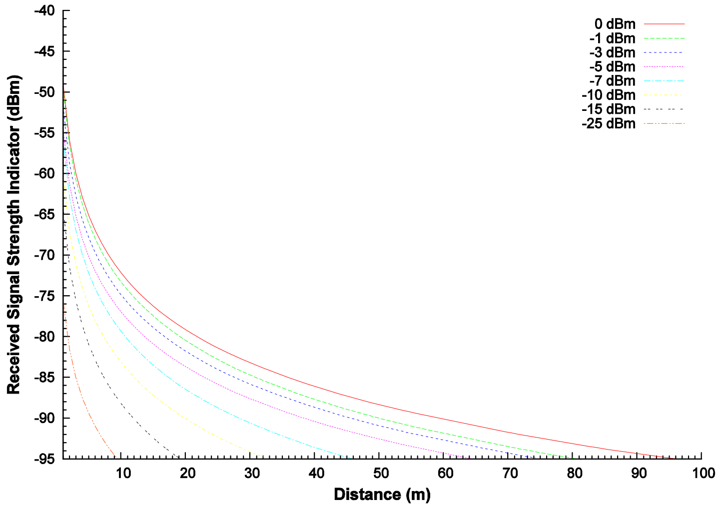


Figure 6.2: Estimated RSSI based upon experimental measurements in an indoor environment

Feasible communication ranges at different transmission power settings can be estimated from Figure 6.2 by using from the fact that TinyOS does not report RSSI when the value is below -95 dBm. An indoor range of up to 96m may be feasible if the maximum power level is used for transmission. A 10m range may be obtained if the sensors transmit at the minimum power. By choosing an appropriate power setting, a direct communication between source and base station is feasible.

The estimations provided in Figure 6.2 are based upon the eight transmission power levels specified in [Tmote]. In TinyOS, the power setting command accepts an integer ranging from 1 to 31. In order to estimate the indoor ranges of all 31 feasible power settings, a regression analysis is conducted and the results are shown in Figure 6.3.

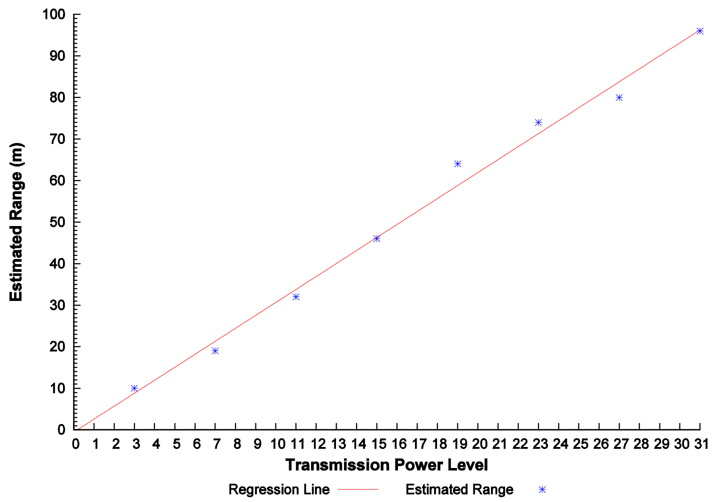


Figure 6.3: Estimated indoor ranges of all feasible power settings

Linear regression is used as it provides an R-square of over 0.99 implying more than 99% of the data can be fitted by the regression line. The results can be used to estimate the indoor communication ranges at different transmission power settings. In order to achieve a higher communication range, a higher power should be used.

An extensive experiment in an outdoor environment was conducted in [SKPP07]. The sources were placed in a free space parking area at varying distances of up to 50m. The heights above ground were respectively set to 2m and 1.10m for the receiver and sender. The average RSSI measurements of 10 distances, 2, 4, 6, 8, 10, 20, 30, 40 and 50m, are used for logarithmic regression analysis. All six power settings, 0, -2.5, -4, -6.5, -10 and -17.5 dBm, are used. The results are shown in Figure 6.4.

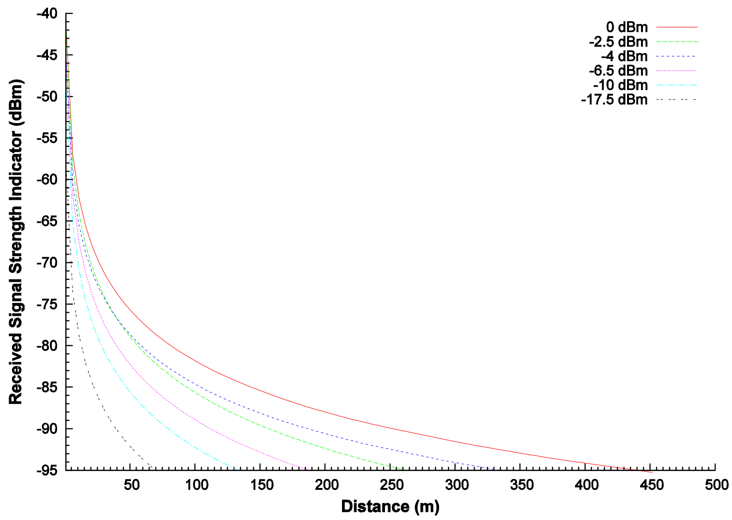


Figure 6.4: Estimated RSSI based upon experimental measurements in [SKPP07]

The R-square values for an outdoor range analysis are at least 0.80 which mean that the regression lines fit at least 80% of the raw data. Communication range increases if the sensors are deployed outdoors. According to Figure 6.4, up to 450m may be achieved at the maximum power setting. However, the communication ranges are affected by several factors, such as trees, buildings and other structures.

The estimations provided in Figure 6.4 are based upon the six transmission power levels selected by [SKPP07]. In order to estimate the indoor ranges of all 31 feasible power settings, a regression analysis is conducted and the results are shown in Figure 6.5.

Linear regression is used as it provides an R-square of over 0.98 implying more than 98% of the data can be fitted by the regression line. The results can be used to estimate the outdoor communication ranges at different transmission power settings.

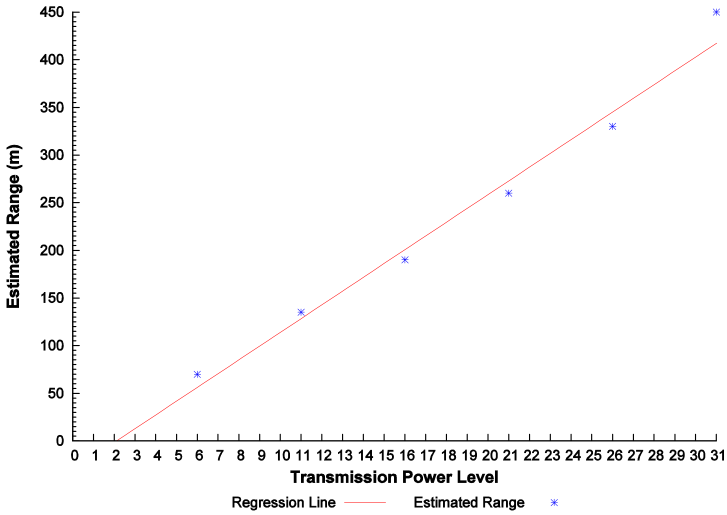


Figure 6.5: Estimated outdoor ranges of all feasible power settings

Experiments were conducted in a parking lot in [LZZ+06]. There are two main differences in the outdoor experimental settings between [LZZ+06] and [SKPP07]. Firstly, a free space parking area was used in [SKPP+07] whilst a non free space parking area was used in [LZZ+06]. The presence of physical barriers therefore existed during the experimentation in [LZZ+06]. Secondly, the heights above ground level were different. The sensors were placed at various heights in [SKPP07] whereas they were on the ground in [LZZ+06]. Similar statistical analyses were repeated on the measurements reported in [LZZ+06] and the results show that the feasible ranges are lower than 10m for all power settings. The differences in the estimated ranges mainly result from the presence of physical barriers and heights of the nodes. Such observations confirm that the measurement-based approach should be used in the adaptive transmission power protocol.

6.3.3 Feasible indoor and outdoor communication ranges

The previous two sections demonstrate the analysis of communication range of sensor based upon the free space propagation model and the estimation of the indoor and outdoor ranges based upon experimental results. The ranges are obtained by determining the RSSI of -95 dBm which is the minimum value which the receiver's transceiver interpret the received signal.

However, packet losses are likely to occur if lower transmission is used to produce the RSSI of -95 dBm. One of the key requirements in data delivery in the network is to minimise data losses. According to the RSSI-PRR relationships in [LZZ+06 and SDTL06], the RSSI of -85 dBm or higher often produces the PRR of nearly 100%. Similar procedures are applied to the results shown in Figure 6.1, 6.2 and 6.4 to estimate the ranges based upon the -85 dBm. As the chosen power levels in [SKPP07] are different from the ones in [CC2420], the estimated outdoor ranges for -95 dBm are based upon the regression line shown in Figure 6.5. The results are shown in Table 6.1. The selected eight transmission powers are specified in [CC2420].

Table 6.1: Feasible communication ranges

Transmission Power		Estimated Communication Ranges (m)					
(dBm)	Level	Free Space Model		Indoor		Outdoor	
		-95 dBm	-85 dBm	-95 dBm	-85 dBm	-95 dBm	-85 dBm
-25	3	65	20	10	2.5	15	10
-15	7	200	70	20	8	70	29
-10	11	390	120	32	12.5	130	48
-7	15	500	180	45	18	190	67
-5	19	650	230	65	24	245	85
-3	23	870	300	74	29	305	105
-1	27	1,000	380	80	33	360	124
0	31	1,000+	420	96	38	420	143

Shorter communication ranges are achieved if -85 dBm is required instead of -95 dBm. This is because the reception strength decreases with longer distances. The free space model gives significant ranges as no barriers and good whether are assumed in the model. The indoor and outdoor ranges are obtained from experimental results in Chapter 4 and [SKPP07], respectively. The indoor and outdoor ranges specified in [Tmote] are respectively 50m and 125m.

Communication range is important in the single-hop network where the nodes require a clear line-of-sight path. Moreover, nodes must be located within the ranges. The estimated values based upon -85 dBm indicate that direct communication can be applied to wireless sensor networks as the sensor has up to 38m indoor and 143m outdoor ranges whilst the packet losses are minimised.

6.3.4 Summary

This section presents a set of statistical analyses in order to explore feasible indoor and outdoor communication ranges. Sensors employ radio communication in which the reception signal strength is affected by several factors such as location and environment. The existing free space propagation model is not sufficient for RSSI estimation. Several recommendations predicting the path loss due to climatic conditions mainly focus on considerably higher operating frequencies system. Logarithmic curve estimation is used to analyse the measurements in Section 4.4.3 and in the reviewed literature [LZZ+06 and SKPP07].

A feasible indoor range of up to 96m is obtained at the maximum power setting. Direct communication is therefore feasible at the longer range setting. A linear regression is used to predict indoor communication ranges of all the feasible power settings in CC2420. The estimation for outdoor measurements in [SKPP07] gives a range of up to 450m. Shorter indoor and outdoor ranges at 38m and 143m are obtained when the RSSI of -85 dBm is used. It often provides the PRR of nearly 100% according to [LZZ+06 and SDLT06].

Considerably different results are observed in [LZZ+06] as only a 10m range can be achieved as the network was set up in a non free space outdoor environment. An adaptive transmission power communication protocol should be measurement-based in order to obtain the optimal link quality. Direct communication can be used in most indoor settings. Further, in an outside environment the range is often quite considerable, although obstacles can cut it drastically. Hence, direct communication is possible in a significant proportion of scenario.

6.4 Preliminary Comparison of Direct and Multi-Hop Communications

In this section, several experiments are conducted in order to compare current consumption between the single-hop and multi-hop scenarios.

Sensors are power and resource constrained, the multi-hop scenario has been advocated for WSNs as it achieves lower transmission power between hops and allows a larger area to be covered. Transmission power is related to the distance and path loss exponent [Hae03, Hae04, HP05 and SBW09]. Multi-hop insignificantly benefits from routing over many short hops in the fading environment, especially when the path loss exponents are small [Hae03]. Short-hop routing minimises the transmission power per transmission but there are some drawbacks to multi-hop communication. The energy consumption required for forwarding data by the intermediate nodes is considerable and is sometimes neglected [SBW09]. Moreover, the sources located near the base station are defined as critical nodes as they have to receive all of the forwarded messages [Hae03]. It is more likely for them to run out of power quickly and the targeted network lifetime may not be met.

Three studies were conducted where the energy requirements for direct and multi hop communication were compared. In each study a line topology was used:

- In the first analysis the network was divided into regions each of which corresponds to a different transmission power setting. One node was placed in each region. The minimum power level is used in the hop-by-hop transmission. The receiving current consumption was also calculated based upon the Tmote datasheet [Tmote].

- In the second analysis the distance between nodes was varied between one and ten metres. The transmission power required for distances was obtained through measurement. Tmote Invent and Tmote Sky were used as sensor and base station, respectively. The base station remained at the same location throughout the experiment whilst three sensors were placed at ten different locations, 1, 2, 3, 4, 5, 7, 10, 13, 16 and 20m, in the same direction with a clear line-of-sight. Each power adaptation cycle was ended after the maximum power had been reached. The sensors transmitted a packet every second. At each power setting, 50 packets were sent. An average was computed and plotted against the distance.

- In the third analysis the effect of varying the density of node distribution was examined.

6.4.1 Preliminary analysis of the benefits of single-hop

Unlike multi-hop, the sources send the data directly to their base station in the single-hop scenario. Data forwarding on to intermediary nodes is thus unnecessary. In order to show the effects of transmissions and receptions on power consumption in both approaches, a line topology is selected as it is able to demonstrate the data forwarding. It is assumed that the data must be forwarded by each of the nodes between the source and the base station. However, the main limitation is that sometimes the edge node may not need to forward all messages and the line topology does not correctly represent the traffic. The routing protocol is responsible for discovering the best path which may be based upon the number of hops or energy consumption.

The line topology shown in Figure 6.6 is used in this comparative study. It consists of eight sources and a base station. There are two assumptions applied. Firstly, each source is assumed to be located at the distance where a particular power level can be used for transmission. According to Tmote and CC2420 data sheets, there are eight transmission power levels; -25, -15, -10, -7, -5, -3, -1 and 0 dBm. Another assumption is that, the minimum power of -25 dBm can be used for hop-by-hop transmissions.

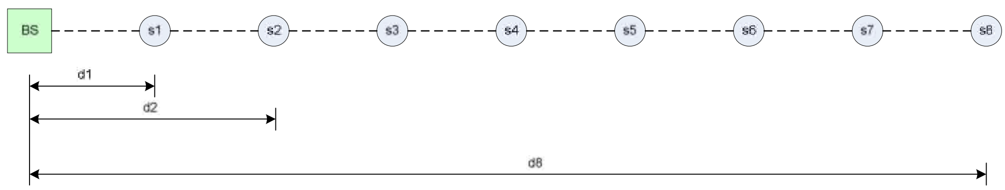


Figure 6.6: Line topology consisting of a base station and 8 sources

According to the first assumption, in the case of single-hop communication, source s1 transmits at -25 dBm whilst source s8 transmits at 0 dBm. The corresponding current required for transmission is 8.5 and 17.4 milli-amps (mA), respectively. The current used for data reception is 19.7mA. The amount of current consumption required by data transmissions and receptions for both single and multi-hop is shown in Figure 6.7.

Several observations can be made about Figure 6.7:

1. The transmission power required by the sources in the single-hop scenario increases with distance as a result of direct communication. The minimum transmission power may be used for hop-by-hop communication.

2. Source s1 consumes the most amount of transmission power as it has to forward all messages delivered from the other sources. The s1 may transmit at the minimum power for the single-hop approach.

3. Considering the receiving current of the sources, the sources in the single-hop network only receive control packet from the base station. They do not receive data packets from their neighbours. Therefore, the 19.7 mA receiving current is consumed by each of the sources.

4. In the multi-hop case, the sources located more closely to the base station consume a greater amount of receiving current.

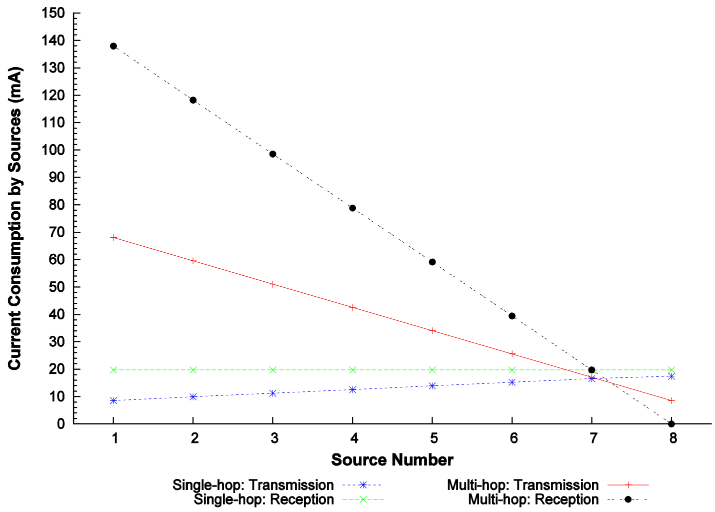


Figure 6.7: Current used for data transmission and reception

In summary, the sources located closer to the base station benefit the most from direct communication as they consume less transmission power. These nodes require more sending and receiving power to accommodate multi-hop communication. The sources which are not responsible for forwarding the packets from their neighbours benefit the most in the multi-hop.

6.4.2 Transmission power and current required for range of distances

The experimental results shown in Figure 4.2 were used to identify the transmission power required for each distance. In total ten distances and three sources were varied and the relationship between the RSSI (Received Signal Strength Indicator) and the distances were established. The maximum distance was 20m, which is less than the indoor range specified in [Tmote]. An outdoor experiment was conducted in [SKPP07]. Packets sent at a lower power than the maximum level from a sender located at 50m away can be received. For example, the RSSI of -90dBm was observed from a transmission power of -17.5 dBm.

As data loss should be minimised, an RSSI providing at least 95% of the Packet Reception Rate, PRR, was used to analyse the maximum distances gained. According to the RSSI-PRR relationship shown in Figure 4.5(a) and [LZZ+06], at least -85 dBm of RSSI meets the mentioned requirement. The transmission power producing at least -85 dBm of RSSI at several distances is provided in Table 6.2. Moreover, the estimated communication ranges obtained from Section 6.3.3 are also included.

Table 6.2: Range of maximum distances supported by transmission power levels

Transmission Power		Required Current (mA) [CC2420]	Additional Current (%)	Maximum Distances (m) from Figure 4.5 (a)	Estimations of Ranges	
dBm	Level				Free Space Model	Measurements
-25	3	8.5	0	1.5 – 4.0	20	2.5
-15	7	9.9	16.5	5.5 – 7.0	70	8
-10	11	11.2	31.8	6.5 – 10.5	120	12.5
-7	15	12.5	47.1	8.5+	180	18
-5	19	13.9	63.5	9.0+	230	24
-3	23	15.2	78.8	9.5+	300	29
-1	27	16.5	94.1	9.5+	380	33
0	31	17.4	104.7	9.5+	420	38

The power levels are represented by 5-bit unsigned integers and are used to set the output or transmission power for the CC2420 radio unit. The required current for each power level is also given in Table 6.1. A higher current is required for longer distances. According to the results, the minimum power level can be used for data transmission up to 4m. The additional current required for longer distances, based upon minimum power usage, is also shown. Data transmission at the maximum power level consumes over 100% more current. The number of hops between source and destination is one of the main factors which affect energy consumption. A significant amount of additional energy is needed in the multi-hop if the packets must be forwarded through the delivery path. The range of current consumption for each topology is presented in the following sections.

6.4.3 Effects of the distances between sources

A 5-hop topology shown in Figure 6.8 is used to investigate how the distance between sources or spacing affects the current consumption required for single and multi-hop communications.

Each source sends a packet which has to be received by all intermediate nodes in the multi-hop case. However, the packet is transmitted directly to the base station in the single-hop case. The spacing, *d*, is set between 1 and 10m. The current required for each distance is obtained from Table 6.2. The analytical results are shown in Figure 6.9.

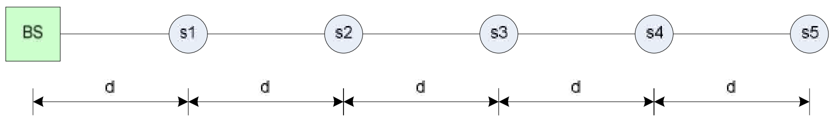


Figure 6.8: A 5-hop network with equal spacing

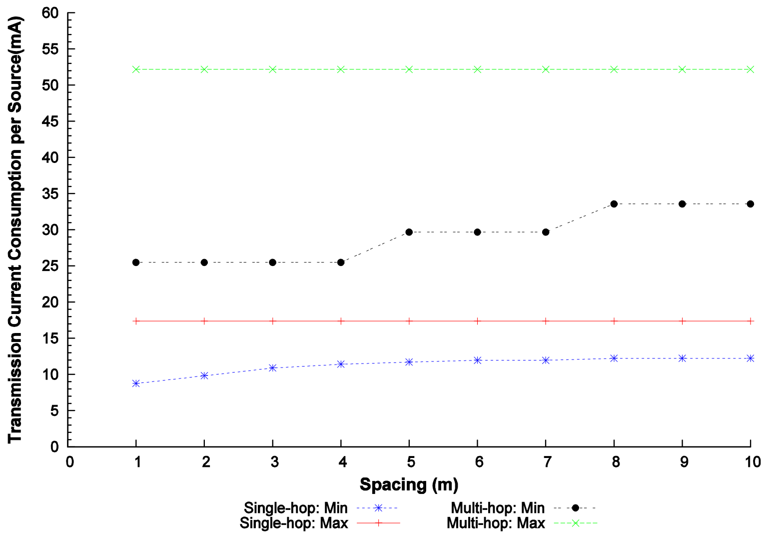


Figure 6.9: Effects of spacing on transmission current consumption

The minimum current shown in Figure 6.9 is based upon the experimental results. There may be some circumstances in which a specific transmission power obtained from Table 6.1 cannot produce the expected RSSI. A higher power is then required for transmission. The maximum power of 17.4mA is therefore included in this study. For the single-hop, the maximum current consumption used for transmission per source is (17.4 mA per transmission * 5 transmissions / 5 sources) or 17.4 mA. However, the necessary power is (17.4 mA per transmission * 15 transmissions / 5 sources) or 52.2 mA in the case of multi-hop communication.

According to Figure 6.9, the amount of current consumption per source increases with the distance between nodes as a higher power is required. The current required approaches the maximum level at greater source spacing. The single-hop requires nearly one-third of the multi-hop current. The main reason is that higher transmissions are required for multi-hop communication. Note that the above results are obtained from the transmission only. An additional 10 receptions are required by the sources in the multi-hop. In [CC2420], each reception requires 19.7 mA. Source s4 has to receive the packet sent by s5. Source s3 has to receive the packet directly sent by s4 and another one forwarded by s4 which was initially sent by s5. In total (1+2+3+4) or ten receptions are required. Hence, an additional (19.7 mA per reception * 10 receptions) or 197 mA is desirable. Only one reception is desired at the base station in the single-hop.

6.4.4 Effects of source densities

This section aims to demonstrate the effects of source density on transmission current consumption. A distance of 50m shown in Figure 6.10 is used as it demonstrates the indoor range of [Tmote]. In total seven different sources are uniformly scattered over a line topology which spans a distance of 50m. Each source transmits its packet to the base station directly in the single hop scenario.

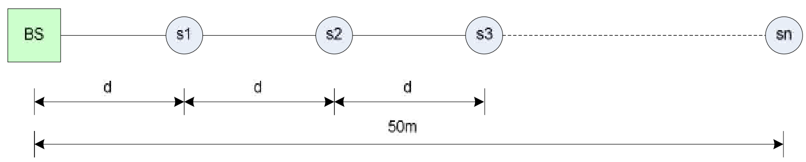


Figure 6.10: A 50m-distance line topology

Each source sends a packet which has to be received by all intermediate nodes in the case of multi-hop. The numbers of sources, n, are set to 1, 2, 5, 10, 20, 50 and 100. The corresponding densities are defined as the number of sources per metre; therefore the densities are 0.02, 0.04, 0.1, 0.2, 0.4, 1 and 2. Both the minimum current based upon the experimental results providing at least 95% PRR and maximum current based upon the full transmission power capability are calculated and shown in Table 6.3.

Table 6.3: Minimum current consumption required for transmissions at 7 source densities

No. of Sources	Density (nodes/m)	Spacing *d* (m)	Single-hop		Multi-hop			
			Min. Current (mA)		No. of Transmissions	Min. Current (mA)		
			Total	Per Source		By Each Source	Total	Per Source
1	0.02	50	12.5	**12.5**	1	12.5	12.5	**12.5**
2	0.04	25	25	**12.5**	3	12.5	37.5	**18.75**
5	0.1	10	61.2	**12.24**	15	11.2	168	**33.6**
10	0.2	5	121.1	**12.1**	55	9.9	544.5	**54.45**
20	0.4	2.5	240.8	**12.04**	210	8.5	1,785	**89.25**
50	1	1	597.3	**11.95**	1275	8.5	10,837.5	**216.75**
100	2	0.5	1,193.3	**11.93**	5050	8.5	42,925	**429.25**

The required transmission power depends upon the distance between source and base station in the single-hop case. In multi-hop, it depends upon the distances between two neighbours. The total current consumption is equal to the summation of the required current for all sources. The current per source is the total divided by the number of sources. In the multi-hop case, the total number of transmissions is also given. The maximum current consumption is computed based upon 0 dBm power. According to Table 6.3, in the single-hop case, the total current consumption increases with the numbers of sources. The total current per source insignificantly decreases as a lower transmission power can be used by the sources located closer to the base station. Therefore, the total current does not constantly increase with the number of sources. In the multi-hop case, the number of transmissions significantly increases with the number of hops. Figure 6.11 shows minimum and maximum current consumption of both single and multi-hop communications in the line topology.

The results demonstrate a significant benefit of direct communication over the multi-hop scenario. The benefit is higher for a denser network in comparison to the required message forwarding of a multi-hop network. However, a source may not be able to conduct direct communication at 50m. According to Table 6.2, a power setting of -7 dBm or lower can be used for a 10m range which means that 5 sources are required in the topology. Each source consumes approximately 12.24 mA compared to the 33.6 mA used by the multi-hop. Hence, almost two-thirds of the transmitting current can be conserved.

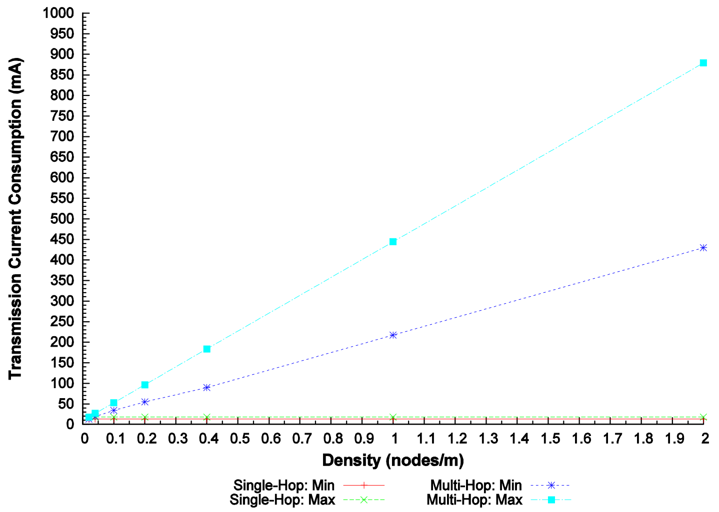


Figure 6.11: Minimum and maximum current consumption in single and multi-hop

6.4.5 Summary

This section aims at investigating feasible communication ranges of sensors and conducting comparative studies between single and multi-hop communications. The free space propagation model is analysed and a set of ideal communication ranges up to a kilometre is obtained. The results are validated by looking at the measurements in the previous chapter and associated literature. Logarithmic curve estimation gives the highest R-square and is therefore used to develop regression lines to estimate RSSI and range. A 96m indoor range can be obtained if the maximum power is set whilst a 10m range is obtained for the minimum power setting. Estimated indoor ranges for all feasible transmission power settings in CC2420 are obtained by linear regression analysis.

A similar study is applied to the outdoor measurements in [SKPP07]. Up to a range of 450m is obtained for the maximum power. Much lower ranges are obtained in [LZZ+06]. This confirms the variability in signal propagation and so the measurement-based approach should be used to determine the current link quality. A -85 dBm RSSI which often produces the PRR of nearly 100% is also used to estimate indoor and outdoor communication ranges. A 38m indoor range can be obtained if the maximum power is set whilst a 2.5m range is obtained for the minimum power setting. Up to an outdoor range of 143m is obtained for the maximum power setting. Hence, direct communication is possible in a significant proportion of scenarios.

The distances between sources and their densities are varied in the comparative studies. Line topology demonstrates the data forwarding in the multi-hop communication. The current consumption per source increases with increasing distance between the sources for both single and multi-hop cases. According to the effect of densities, significant increases in the consumption are observed in the multi-hop when more sources are used for message forwarding. However, the current consumption in the single-hop slightly decreases.

The sources significantly benefit in the single-hop case when the source density is high. In the case where 5 sources are uniformly distributed over a 50m line topology, almost two-thirds of the transmitting current can be conserved if single-hop is used. More current will be saved in a higher density network as the number of message forwarding increases.

6.5 Transmission Power Adaptation, Reliability and Energy Conservation

The Power & Reliability Aware Protocol (PoRAP) is developed in this dissertation. PoRAP aims to provide an efficient communication mechanism for wireless sensor networks (WSNs) in terms of energy conservation and reliability awareness. The previous section demonstrates the viability of direct communication in WSNs. PoRAP is an adaptive transmission power protocol allowing lower power to be used for transmission without impacting on reliability.

This section describes experimental studies which test the power adaptation capability of PoRAP. There are two experiments. The first focuses on testing whether PoRAP correctly adjusts the transmission power and investigates the transmission power required for each cycle. In total 20 Tmote Sky sources were placed at 20 separate locations with 14 different distances to address the effects of location. A Tmote Sky base station broadcasts the control packet at the maximum power at the start of each communication cycle. Each source is allocated to a time slot when it can send. After the control packet has been received, a source transmits its data at the maximum power. The base station receives data and decides whether the current power of each source requires adaptation. The communication proceeds for 1,000 cycles. The source should correctly adjust its power corresponding to the notification generated by the base station.

The second experiment investigates the effects of different RSSI settings for PRR and energy consumption. Sensors are power and resource constrained so data transmission at the maximum power level may provide the required reliability but no conservation of energy can be achieved. However, a lower power may be used but the required reliability may not be met. The main objective of the second experiment is to discover the optimal point at which both energy conservation and reliability can be obtained.

6.5.1 Parameter settings

The experiment was conducted in a 16m x 20m laboratory room. A network consisting of 20 sources and a base station was set up. Tmote Sky motes were used as both sources and base station. The sources were placed at 20 different locations with 14 different distances and the base station was connected to a desktop machine. All motes had the same height above ground level and had the same antenna orientation. The minimum and maximum distances are 1 and 22.5m, respectively. In total 6 pairs of motes were placed at different distances in order to investigate location effect. Figure 6.12 graphically shows the locations of sources and base station.

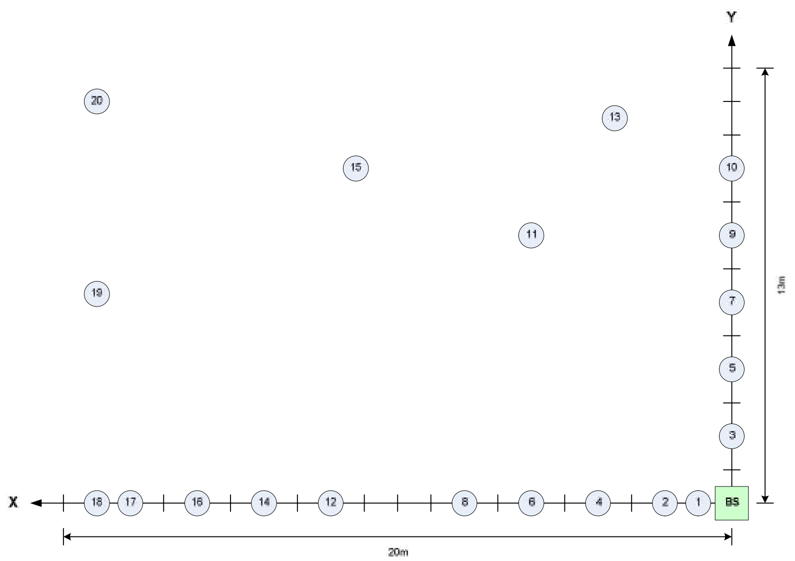


Figure 6.12: Locations of 20 sources and base station

Table 6.4 shows coordinates and distances of the sources. The *X*, *Y* and *D* represent the *x*, *y* coordinates and distance respectively.

Table 6.4: Coordinates and distances of sources (m)

Mote	X	Y	D	Mote	X	Y	D	Mote	X	Y	D	Mote	X	Y	D
1	1	0	1	**6**	6	0	6	**11**	6	8	10	**16**	16	0	16
2	2	2	2	**7**	0	6	6	**12**	12	0	12	**17**	18	0	18
3	0	2	2	**8**	8	0	8	**13**	3.5	11.5	12	**18**	19	0	19
4	4	0	4	**9**	0	8	8	**14**	14	0	14	**19**	19	6.2	20
5	0	4	4	**10**	0	10	10	**15**	11.2	10	15	**20**	19	12	22.5

Initially, the base station broadcast its 18-byte control packet to the sources. The sources then transmitted the 48-byte data packets back to the base station. A communication cycle was completed after the base station had received the data from all sources. The next cycle was started in the next 5 minutes as in [MPS+02] and [TPS+05]. In total a thousand cycles were run. The minimum and maximum RSSI thresholds were respectively set to -90 and -80 dBm.

The transmission power was increased if the measured RSSI was equal to or less than the minimum. However, it was decreased when the RSSI was equal to or greater than -80dBm. Otherwise the sources maintained their current power. The sources sent their first data packets in the first cycle at the maximum level. The power was changed by 4 such as from 3 to 7 if an adaptation was required. This means that eight different power levels provided in the CC2420 and Tmote data sheets, 3, 7, 11, 15, 19, 23, 27 and 31, are used in this experiment.

6.5.2 Results

Some of the experimental results including adjusted transmission power, packet reception rate and energy conservation are provided in this section.

A) First experiment - Transmission power adaptation and RSSI

Figure 6.13 shows the adapted transmission power (TX) levels of 6 motes located at 3 different distances (2, 6 and 10m). Mote 2 and 3 are considered as the first and second locations of the 2m distance. In the case of the 6m and 10m locations, Motes 6 and 10 are considered as the first whereas Motes 7 and 11 are the second locations, respectively.

The main reason why only three different distances are presented in Figure 6.13 is that they are sufficient to demonstrate the effect of locations on the adaptive power settings. The same power does not always produce the same range of RSSI at the same distance. Further, the results of other sensors demonstrate similar observations. In order to investigate the frequencies of power settings used by each node, the ratio of transmission power frequency to the number of total readings is calculated and shown in Table 6.5. The summation of the output for each mote is equal to 1.

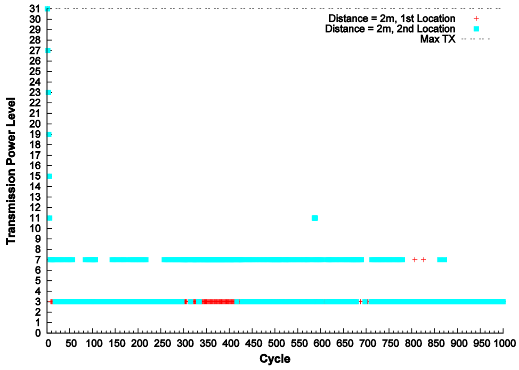
According to Figure 6.13 and Table 6.5, several observations can be made as follows:

1. Different transmission power levels are required for different motes in order to produce the desired RSSI of between -90 and -80 dBm.

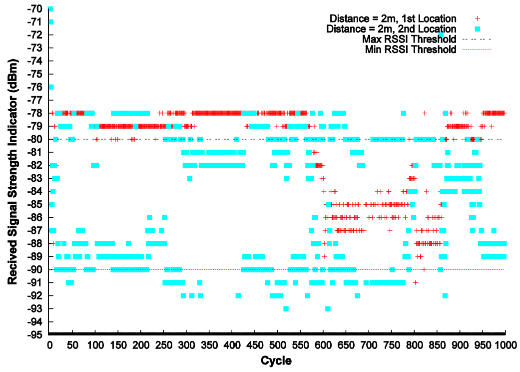
2. Location affects the RSSI. For example, Mote 2 and Mote 3 were placed 2m away from the base station. A higher power level of between 3 and 7 was often used by Mote 3

whilst the minimum power level of 3 was mostly used by Mote 2 throughout the experiment.

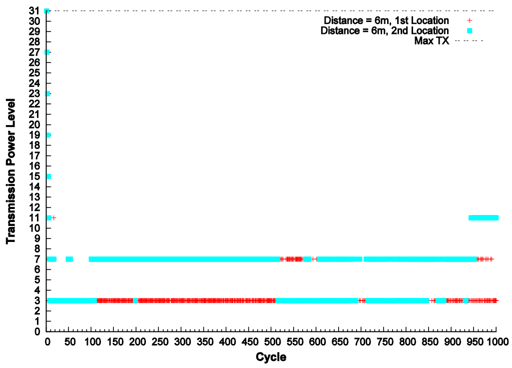
3. PoRAP's transmission power adaptation capability performs correctly as most of the RSSI measurements are within the desired range. However, there may be some cases where the RSSI values are outside the range. For example, the minimum power has been reached and the RSSI values remain greater than the maximum threshold as no further reduction of current power cannot be made.



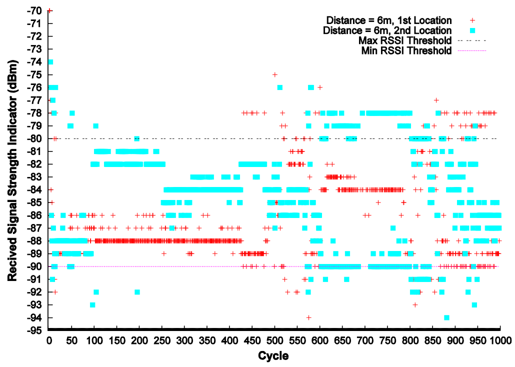
(1a) TX level at the 2m locations



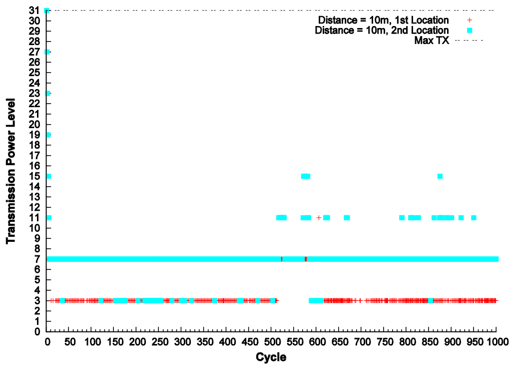
(1b) RSSI at the 2m locations



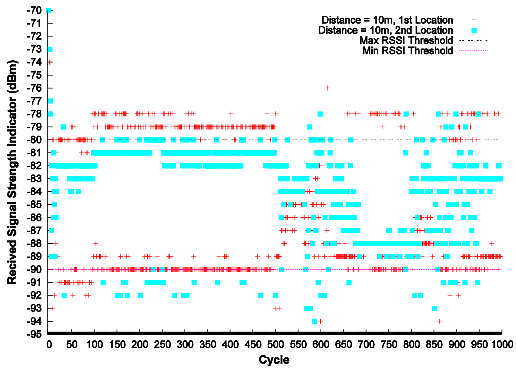
(2a) TX level at the 6m locations



(2b) RSSI at the 6m locations



(3a) TX level at the 10m locations



(3b) RSSI at the 10m locations

Figure 6.13: transmission power adaptation and RSSI at 3 different distances

4. Transmitting at a higher power level may not always result in a greater RSSI as the link quality changes over time. For example, a higher RSSI may be observed if there are no temporary barriers such as students walking around the laboratory.

5. According to the results, the minimum RSSI measurement was -94 dBm. The CC2420 specifies the receiving sensitivity at -95dBm. Therefore, measured RSSI values lower than -95dBm, upon data packet reception, are not reported by the base station's transceiver.

Table 6.5: Ratio of TX frequencies to the number of readings

Mote	Dist. (m)	Transmission Power (TX) Level							
		3	7	11	15	19	23	27	31
1	1	0.993	0.001	0.001	0.001	0.001	0.001	0.001	0.001
2	2	0.991	0.003	0.001	0.001	0.001	0.001	0.001	0.001
3	2	0.591	0.400	0.004	0.001	0.001	0.001	0.001	0.001
4	4	0.473	0.521	0.001	0.001	0.001	0.001	0.001	0.001
5	4	0.579	0.363	0.053	0.001	0.001	0.001	0.001	0.001
6	6	0.846	0.146	0.003	0.001	0.001	0.001	0.001	0.001
7	6	0.290	0.646	0.059	0.001	0.001	0.001	0.001	0.001
8	8	0.232	0.105	0.644	0.012	0.004	0.001	0.001	0.001
9	8	0.706	0.287	0.002	0.001	0.001	0.001	0.001	0.001
10	10	0.554	0.439	0.002	0.001	0.001	0.001	0.001	0.001
11	10	0.045	0.890	0.051	0.010	0.001	0.001	0.001	0.001
12	12	0.297	0.665	0.025	0.007	0.003	0.001	0.001	0.001
13	12	0.050	0.804	0.140	0.001	0.002	0.001	0.001	0.001
14	14	0	0.039	0.270	0.155	0.027	0.015	0.116	0.378
15	15	0	0.071	0.726	0.077	0.023	0.019	0.083	0.001
16	16	0	0.269	0.160	0.524	0.024	0.021	0.001	0.001
17	18	0	0.435	0.346	0.038	0.087	0.048	0.039	0.007
18	19	0	0.037	0.700	0.200	0.025	0.010	0.006	0.002
19	20	0	0.525	0.265	0.050	0.114	0.031	0.014	0.001
20	22.5	0	0.123	0.230	0.528	0.086	0.017	0.011	0.005

PRR is also important as it is directly related to the reliability. Some data packets are received by the base station's radio but they are not delivered to its upper layers as the observed RSSI values are lower than the sensitivity threshold (-95 dBm). The feasibility of misinterpreting the received signal is high in such case and the data packet is discarded by the base station's transceiver.

In the best case where no packets are lost, both the counts of control and data transmissions are equal. There are two cases of packet loss. Firstly, the control packet is lost if a number of sent control packets is lost but the number of associated sent data packets is *orderly* incremented. The number of control packet losses is therefore the difference between the counts of transmitted control and data packets. Secondly, data packet loss occurs if some data packet sequence numbers are skipped. Table 6.6 shows the percentages of control packet loss and PRR of all the motes.

Table 6.6: Percentages of control packet loss and PRR

Mote	Control Packet Loss (%)	Data PRR (%)	Mote	Control Packet Loss (%)	Data PRR (%)
1	0	96.4	**11**	0	90.9
2	0	94.1	**12**	0.3	88.8
3	0.1	90.6	**13**	0.2	91.0
4	0	93.4	**14**	7.5	88.0
5	0.3	89.6	**15**	3.5	89.6
6	0	88.3	**16**	3.2	91.1
7	0	88.3	**17**	4.8	91.7
8	3.7	72.2	**18**	3.9	92.5
9	0.1	90.4	**19**	4.2	92.2
10	0	90.2	**20**	4.3	92.1

In WSNs, data is delivered wirelessly. Data loss is likely to occur if the link quality is low. This experiment was conducted in the laboratory where teaching and student practical work took place. Staff and students can be considered as temporary barriers and may therefore cause packet losses.

According to Table 6.6, the control packet loss is less than the data packet loss as the control packets are broadcast at the maximum transmission power. Mote 1 has the highest PRR as it was located 1m away from the base station. Mote 20 was placed at the farthest location and it has a higher PRR than some nearer motes. Mote 8 has the lowest PRR as it was placed near the printer. Some students stand there to collect their documents and they become physical barriers during data transmission.

Most of the PRR values shown in Table 6.5 are approximately 90% or higher. Such results confirm our experimental results and those in [LZZ+06] and [SDTL06] which indicate that RSSI values between -90 and -80 dBm produce a PRR of approximately 90%. A similar observation of RSSI-PRR relationship in different environments including a corridor, parking lot and grass field is observed in [LZZ+06] and it implies that the RSSI settings can be used in different environments. However, the required power settings which produce a specific RSSI range are dependent upon the environment.

B) Second experiment – RSSI settings, PRR and energy conservation

In PoRAP, the base station broadcasts its control packets using the maximum transmission power whilst the sources send their data packets at the adapted power levels. Both control and data packet losses are feasible. In this experiment, control and data packets were numbered. The sources sent only after they had received the control packet. The numbers were incremented prior to transmission. Both numbers could be observed if the base station received the data packets. Furthermore, the base station was booted after the sources. Hence, the sources should receive the first control packet.

Apart from the maximum power settings, four additional RSSI settings are included. The minimum RSSI thresholds were set to -90, -80, -70 and -60dBm whereas the corresponding maximum thresholds were -80, -70, -60 and -50dBm, respectively. The power is not adapted if the measured RSSI is between the thresholds and the aim is to obtain nearly 100% PRR. Each mote transmitted every 5 minutes and the experiment lasted for 24 hours. The PRR results are shown in Figure 6.14.

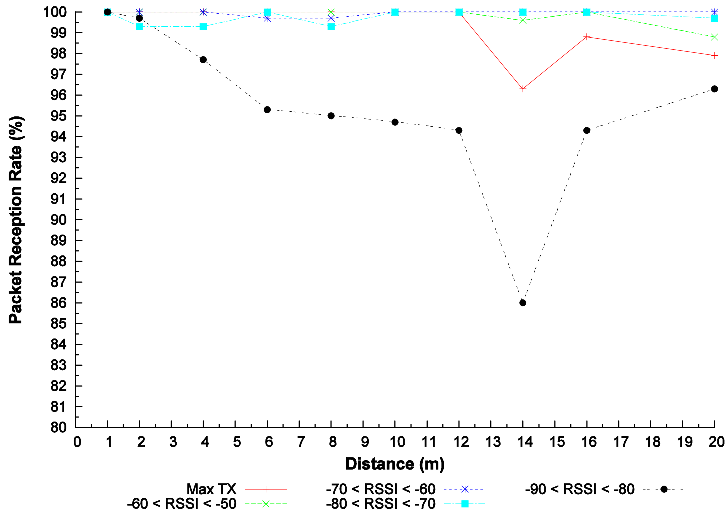
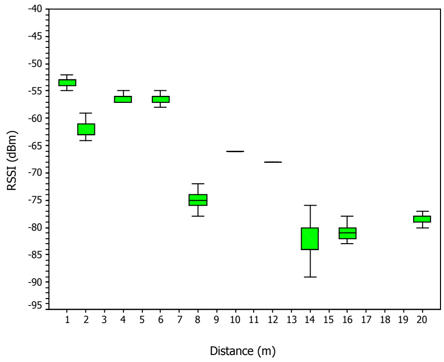


Figure 6.14: Relationship between RSSI settings and PRR

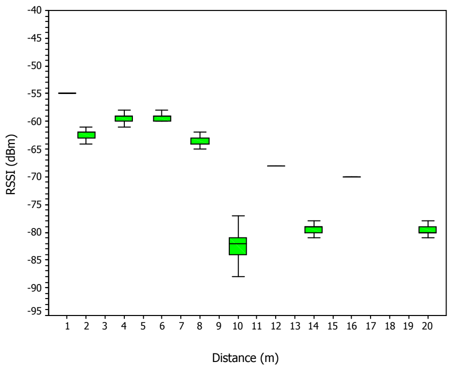
The RSSI values except those between -90 and -80 dBm produce a PRR of nearly 100%. In the case of -60 dBm < RSSI < -50 dBm, the observed PRR values are at least 98.8%. Similar results are obtained in the case of all motes sending at the maximum power. The 100% PRR was obtained at distances up to 12m. The PRR declines at longer distances and a lower PRR was obtained if lower RSSI thresholds were set.

Figure 6.15 and 6.16 shows the box plots of RSSI measurements and five curve fitting techniques of transmission power levels for all the varied distances at different RSSI settings.

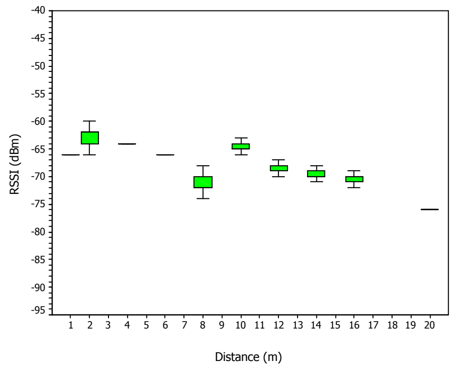
The maximum transmission power at 31 or 0 dBm was used in Figure 6.15 (a). The RSSI decreases with longer distances. In the case of power adaptation, the targeted RSSI may not be met as distance also impacts the received signal strength. For example, the RSSI values between -60 and -50d Bm could not be obtained at distances longer than 8m even the if maximum TX was used in Figure 6.15 (b). For lower RSSI thresholds, the motes located nearer to the base station cannot produce the required range. For example, an observed RSSI of over -80dBm was produced by the motes located at 1m and 2m. These motes mostly transmitted at the minimum TX.



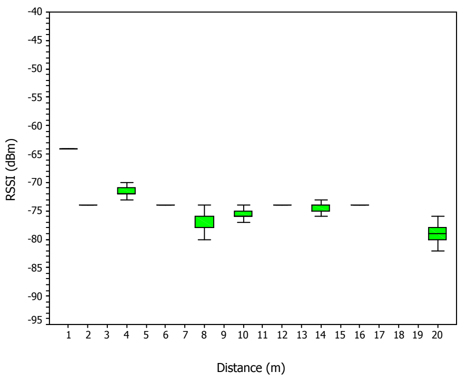
(a) Max TX



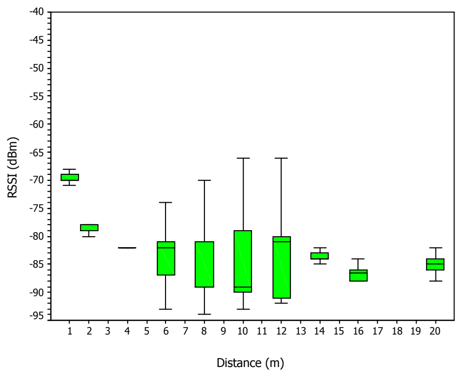
(b) -60 < RSSI < -50



(c) -70 < RSSI < -60

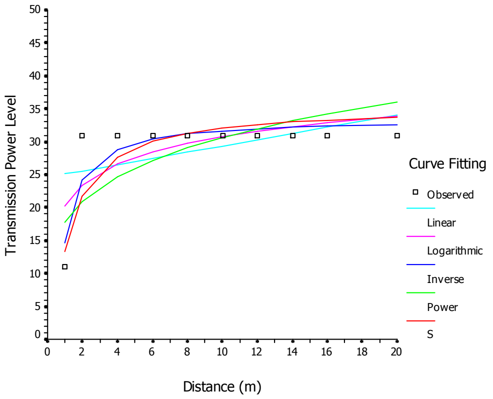


(d) -80 < RSSI < -70

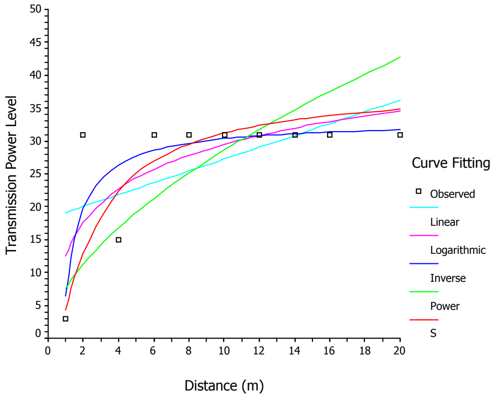


(e) -90 < RSSI < -80

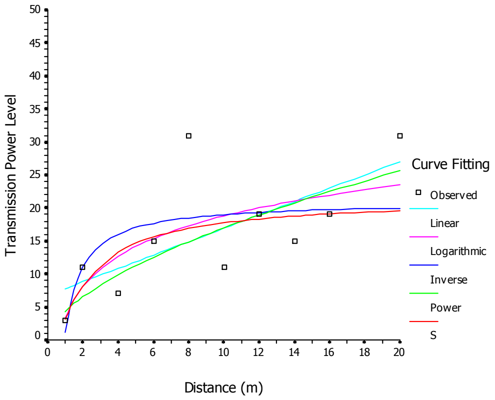
Figure 6.15: Measured RSSI at various distances



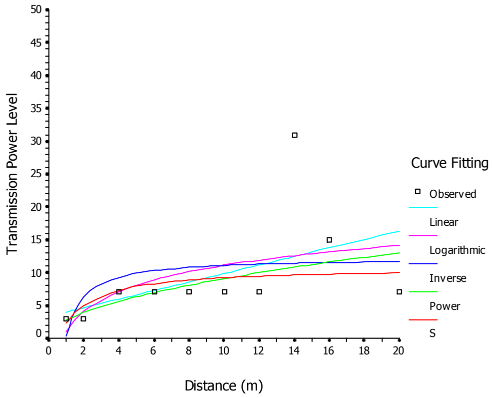
(a) -60 < RSSI < -50



(b) -70 < RSSI < -60



(c) -80 < RSSI < -70



(d) -90 < RSSI < -80

Figure 6.16: Transmission power level required for various RSSI settings

In total five curve fitting techniques provided by the widely used statistical tool SPSS are used to demonstrate the relationship between transmission power and distance. According to Figure 6.16, Linear and Power techniques are not appropriate when the RSSI settings are high such as between -70 and -50 dBm. The main reason is that a higher power or the maximum is often required to meet the RSSI requirement. Such techniques can be used for lower RSSI settings as a lower power can be used for most of the distances and there are some increases in the power which can be conducted. The remaining three techniques of Logarithmic, Inverse and S are more suitable for all RSSI settings. Cliffs in the plots can be observed from the high settings in Figure 6.16 (a) and (b) whilst a linear relationship between transmission power and distance can be seen in the lower settings.

The higher power used by farther motes may not produce the required RSSI as location also impacts on the received signal strength. A lower data packet reception rate (PRR) is produced if lower RSSI thresholds are set. The motes can conserve transmitting energy but some packets may be lost. Transmitting data at the maximum power may result in 100% PRR but no transmitting power is saved. Table 6.7 shows the percentage of conserved transmitting current and data packet loss at various distances and RSSI settings. The medians of transmission power used by the motes are used for the calculations. The required current for transmission power is obtained from the CC2420 data sheet.

The motes located near the base station benefit from the transmission power adaptation as they can transmit at a lower power. The motes conserve energy by decreasing their transmission power levels whilst the RSSI thresholds and corresponding PRR are met. In the case of the lowest RSSI requirements, the motes save more energy but more data packets are lost. The RSSI between -80 and -70 dBm provides an optimal point where the most transmission power can be saved at most distances and the packet losses are less than 1%. However, a higher power can be used to achieve a higher PRR but less energy is conserved. The PRR of nearly 100% is often provided by the RSSI over -70 dBm. The results confirm that there is an optimal area where up to 50% of transmission energy can be conserved while almost 100% of the PRR can be maintained.

Table 6.7: Conserved transmitting current and data packet loss

Dist. (m)	-90 < RSSI < -80		-80 < RSSI < -70		-70 < RSSI < -60		-60 < RSSI < -50		Max TX	
	Saved Trans Current	Packet Loss (%)	Saved Trans Current	Packet Loss (%)	Saved Trans Current	Packet Loss (%)	Saved Trans Current	Packet Loss (%)	Saved Trans Current	Packet Loss (%)
1	51.2	0	51.2	0	51.2	0	35.6	0	0	0
2	51.2	0.3	35.6	0.7	0	0	0	0	0	0
4	43.1	2.3	43.1	0.7	28.2	0	0	0	0	0
6	43.1	4.7	28.2	0	0	0.3	0	0	0	0
8	51.2	5	0	0.7	0	0.3	0	0	0	0
10	51.2	5.3	35.6	0	0	0	0	0	0	0
12	51.2	5.7	20.1	0	0	0	0	0	0	0
14	0	14	28.2	0	0	0	0	0.4	0	3.7
16	28.2	5.7	20.1	0	0	0	0	0	0	1.2
20	43.1	3.7	0	0.7	0	0	0	1.2	0	2.1

According to Table 6.7, lower RSSI settings result in higher percentage of packet loss and conserved transmitting power. Lower power is used to produce the required RSSI range. A significant amount of power up to 50% can be yielded. However, the highest packet loss is obtained when the RSSI is between -90 and -80 dBm.

One of the key requirements in development of network protocol is to minimise the data loss. It can be yielded by always transmitting at the maximum power. The “Max TX” column illustrates such scenario. No power is saved and the packet losses are low. However, it is feasible to use lower power without unnecessary data losses.

For example, the RSSI between -60 and -50 dBm produces a 35.6% of conserved power at 1-m distance with low data losses at greater distances. Higher power conservation is achieved if lower RSSI is set. The appropriate RSSI settings mainly depend upon the reliability requirement. Assuming that a network topology consisting of 10 sources located at 10 different distances as shown in Table 6.7, the application requires at least 99% of reliability at the base station. The maximum power can be used at all sources but no power is saved. The appropriate RSSI setting is between -80 and -70 dBm. With such setting, almost all nodes can conserve their transmitting current. An average power saving of 26.2% per source is achieved. It means that, with such RSSI setting, the sources use an average 73.8% of the maximum power.

6.5.3 Summary

This section describes the experimental details and the results show that the transmission power adaptation works correctly. Most of the RSSI measurements are within the desired range. Another set of experiments provides the results which demonstrate that there is an optimal region where lower power can be used for data transmissions whilst reliability is maintained at nearly 100%. A higher power can be used but less or no energy can be conserved. The sources may send at a lower power to save energy but higher data losses are observed. The RSSI over -70 dBm often produces the RSSI of nearly 100% and 50% of transmission energy is conserved.

6.6 Scheduling - Measurements of Clock Drifts

PoRAP adopts the schedule-based approach where the communication frame is divided into several time slots. A transmission slot is allocated to each source. There are two occasions when the source starts its radio; control packet reception and data packet transmission otherwise the source stops the radio. Data collisions and idle listening can therefore be avoided and minimised in this approach. An important requirement is time synchronisation amongst the nodes. In PoRAP, the sources have to synchronise their local clocks with that of the base station.

A sensor has an oscillator which generates timing signals or ticks. The number of ticks generated in 1 second depends upon the timer interface provided in TinyOS. In this study, a 32-KHz clock is selected and it provides 32,768 ticks per second. Clock drift occurs as a result of uncertainty in the ticking rate. Different local clocks may run at different speeds. Clock drift may be accumulated and time synchronisation is no longer maintained. Clock drift is crucial in a schedule-based system like PoRAP. The control packet is broadcast at the beginning of each frame or communication cycle to decrease the effects of clock drift.

This section provides the details of clock drift measurements. In total 20 Tmote Sky sources were used and they transmitted data to the base station every 5 minutes. The base station measured the clock drifts and a statistical analysis was conducted. The results were compared to the 20 parts per million (ppm) which is recommended in [CMR200]. Further, the durations between two consecutive transmissions were varied to determine the effects. The results are analysed to explore how the prediction of clock drifts relate to further minimisation of idle listening.

6.6.1 Calculation of clock drift

The 20ppm is suggested by the crystal oscillator data sheet [CMR200]. In the preliminary experiment, sources send every 5 minutes, approximately every 10 million ticks. Hence, the clock drift would be 200 ticks. The reserved duration for clock drift should be added to the base station's schedule instead of the sources. The sources benefit from the deferred schedule at the base station as they will not miss the control packet reception and the data packets will be sent at the appropriate time. However, the sources have to listen longer for control packet reception if the extra time is added to their schedules. The source's local clock is not adjusted in PoRAP as it requires either additional local time exchanges between sources and base station or additional information in the control packet. The control packet will be longer if there are many sources in the network. A longer packet may be corrupted during delivery and the sources may receive incorrect information.

For each control packet delivery, the times when its Start of Frame Delimiter (SFD) is transmitted at the base station and received by the sources are measured and stored in the control and data packets. The difference between two local times is computed by the base station after the data packet is received. Additional bytes are required for these timestamps. The clock drift is defined as the difference between the two successive differences in the local clocks. In the case where clock drift does not occur, the time differences should be the same.

Some data packets may be lost during transmissions or they may be discarded by the base station when the observed RSSI is lower than -95 dBm. In such cases, the base station is not able to read the time of packet reception. The duration between two consecutive successful transmissions is thus larger than 5 minutes. Only clock drifts which are calculated based upon the 5-minute interval are used in this analysis.

6.6.2 Results

Table 6.8 shows the results of statistical analysis of clock drifts. Note that the magnitude of clock drift is in ticks.

Table 6.8: Results of statistical analysis of clock drift

Mote	Clock Drift (ticks)						
	Min	Percentile					Max
		10th	25th	50th	75th	90th	
1	0	3	8	11	16	20	24
2	1	16	21	24	28	32	37
3	0	3	7	11	16	21	26
4	147	163	168	172	176	181	186
5	24	42	47	50	55	59	63
6	1	17	22	26	30	34	39
7	10	24.4	32	36	42	47	52
8	4	12	19	22	25	29	36
9	0	3	9	12	18	23	27
10	28	45	51	55	61	67	72
11	12	29	34	37	41	45	54
12	39	51	60	64	68	74	78
13	5	21	27	31	36	40	45
14	0	2	3	6	10	15	20
15	0	3	6	9	15	19	24
16	11	27	32	36	40	45	72
17	2	12	22	25	30	35	40
18	0	9	16	20	24	29	33
19	3	16	25	28	33	38	43
20	0	4	12	16	22	28	50

According to Table 6.8, each mote has a different clock drift. Mote 4 has the highest drift but it is less than 20ppm suggested by the data sheet. The median of Mote 4's drift is 172 ticks which is equal to 17.2ppm or 86% of the suggested value. On the other hand, Mote 14 has the minimum median at 6 ticks which is 30%. It can be concluded that the clock drift is hardware-dependent and non-deterministic. The 20ppm should be used for clock drift and the additional duration should be added to maintain time synchronisation. Figure 6.17 shows the box plots of clock drifts in an ascending order.

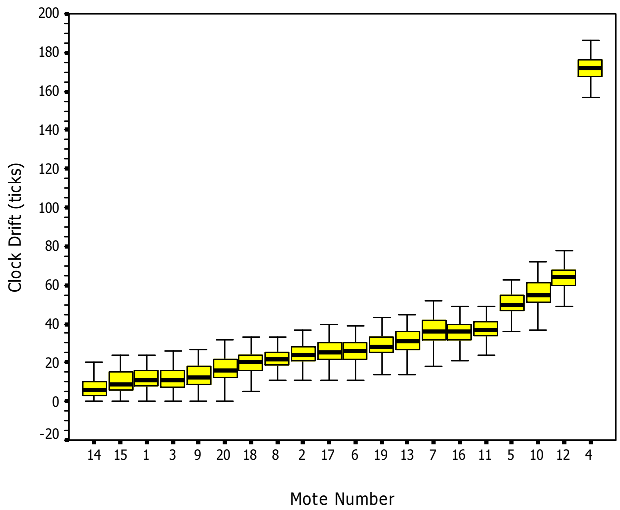


Figure 6.17: Box plots of observed clock drifts

Figure 6.18 demonstrates the distribution of variations in the clock drifts of all sources. The variations of each mote are equal to the difference between the observed drifts and their median. The probability is the ratio of variation occurrences and the number of observed drifts.

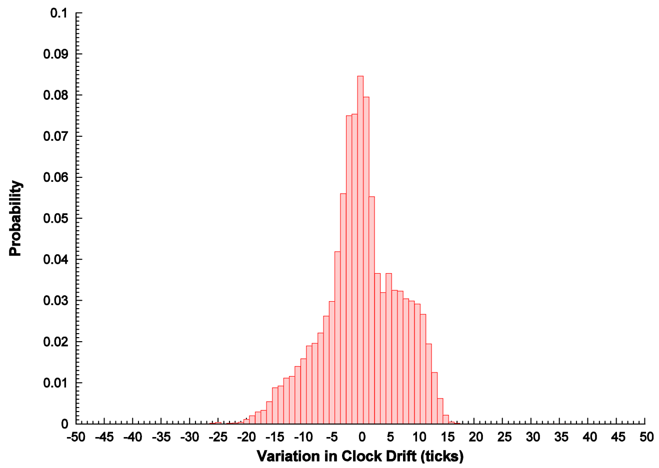


Figure 6.18: Distribution in variations in clock drifts

According to Figure 6.18, the variations range from -27 to 36. The variations between -15 and 15 have probability of 0.01 or higher. Therefore, smaller variations in clock drifts are more likely to occur. The highest probability of 0.085 is observed when there is no variation in the drift. The results demonstrate that, by knowing the median of clock drifts, less than 20ppm can be added into the slot and frame lengths. For example, the sources may defer their schedules by the medians if their clocks run more quickly than the base station's clock. An addition of 63 ticks, the width of the variations, can be added to the frame length to accommodate the drifts. Without a determination of the variations, 200 ticks should be added in the case of 5 minute, or approximately 9.8 million ticks, scheduled transmissions. Therefore, about 68% of duration can be saved for additional transmissions.

The results summarized in Figure 6.18 are based upon 5minute data transmissions. The same computational procedures are repeated in order to investigate how the variations are affected by the durations between two consecutive transmissions.

Table 6.9: Variations in clock drift

Duration	Ticks ($*10^6$)	Range of Variations		Width (ticks)	20ppm	Saved (%)
5 minutes	9.8	-27	36	63	196	68
10 minutes	19.6	-47	37	84	392	79
1 hour	118	-249	200	449	2,360	81
1 day	2,831	-1620	940	2560	56,620	95

The box plots shown in Figure 6.17 indicate that clock drift is hardware dependent. An increase in the width of variations is observed in Table 6.9. Clock drift is also dependent upon duration between transmissions. The "20ppm" column demonstrates the reserved duration which is recommended by the data sheet. By knowing the drift medians, the motes can adjust their schedules in order to synchronise with the base station. The motes start their radios later if their clocks are running more quickly and they can be in sleep mode longer. The idle listening period is therefore reduced. Therefore up to 95% of idle listening, due to reserved time for clock drift, can be reduced. The sources spend less energy on idle listening whilst time synchronisation is maintained.

6.6.3 Summary

This section describes the measurements of clock drifts which are important in a schedule-based approach like PoRAP. Time synchronisation between nodes is no longer maintained if the effects are not taken into consideration. Data collisions may occur and reliability may not be achieved as the sources may miss the correct transmission time. The data sheet of oscillator recommends that 20ppm should be reserved but clock drift is hardware-dependent and the maximum measurement is less than 20ppm. Drift also depends upon the duration between two consecutive transmissions. The measurements demonstrate that clock drift can be accounted for in the scheduling algorithm as it happens in a predictable way by looking at its median and variation. Hence, by measuring variation in clock drift the accuracy with which scheduling can occur is established. The base station monitors the relative clock drift to each of the sources. Such measurements are broadcasted to the sources and they can adjust their scheduling locally to keep the idle listening period minimum. According to the measurements, up to 95% of the reserved duration and the corresponding idle listening energy can be conserved.

6.7 Conclusion

This chapter has provided the details of PoRAP evaluation by means of energy conservation. Unlike traditional multi-hop protocols, PoRAP is specifically developed for applications where direct communications between sources and base station are feasible. According to the transceiver's data sheet, the sensors have 50m and 125m indoor and outdoor ranges. The feasible communication ranges with which direct communication can occur are analysed. The relationships between transmission power settings, RSSI and distance are established. The RSSI of -95 dBm is used to explore the feasible distances. The receiver's transceiver does not receive and interpret the incoming signal if the observed RSSI is lower than -95 dBm.

In the first analyse, the free space propagation model was used and the results show that over 1 kilometre range can be achieved. However, clear delivery path and good environment are assumed in such model. Another analysis is required and it is conducted based upon the measurements in Chapter 4 and associated literature. The experimental results in Chapter 4 are used to obtain the feasible indoor ranges whilst those in [SKPP07] are used for the outdoor ranges. Logarithmic approach provided the highest R-square values of over 0.85 and 0.85 for indoor and outdoor ranges, respectively. It means that over 85% and 80% of the indoor and outdoor measurements can be fit by the scheme. According to the results, up to 10-m and 96-m indoor ranges are possible if the minimum and maximum power levels are respectively used. In the case of outdoor ranges, up to 54m and 450m are obtained. Further, the relationships between ranges and all possible power settings are established with the R-square over 0.98.

Although the -95 dBm is used to establish the feasible ranges, packet losses are likely to occur. The -85 dBm is also used as it often produces the PRR of nearly 100% according to [LZZ+06]. Another set of possible indoor and outdoor ranges are obtained without unnecessary packet loss. Up to 38m indoor and 143m outdoor ranges can be achieved whilst the packet losses are minimized. Thus, direct communication is possible in a significant proportion of scenarios.

Several experiments were conducted to compare current consumption between the single-hop andmulti-hop scenarios. In the first analysis, the network was divided into regions each of which corresponds to a different transmission power setting. One node was placed in each region. The nodes located closer to the base station benefit the most from direct communication. These nodes require more sending and receiving power for message forwarding in the multi-hop. The distance between nodes was varied between one and ten metres in the second analysis. The transmission power required for distances was obtained through measurements in the previous chapter. The amount of transmitting current consumption per source increases with the distance between nodes as higher power is required. The single-hop requires nearly one-third of the multi-hop current. The effect of densities was examined in the third analysis. In total seven different sources were uniformly scattered over a line topology which spans a distance of 50m.The sources significantly benefit in the single-hop when the source density is high. In the case where 5 sources are uniformly distributed, almost two-thirds of the transmitting current can be conserved if the single-hop is used.

A set of experimental studies was set up to test the transmission power adaptation capability of PoRAP. In total 20 Tmote Sky sources were placed at 20 separate locations with 14 different distances. There are two experiments. The first focuses on testing whether PoRAP correctly adjusts the transmission power and investigates the power required for each cycle. The results demonstrate the importance of locations. The same power is not always used at the same distance but different locations. The power adaptation works correctly as most of the RSSI measurements are within the desired range. The minimum RSSI was -94 dBm which is closed to the -95 dBm specified in [CC2420]. The control packet losses were less than those of data packet as the control packet was always broadcasted at the maximum power. The results confirm those in [LZZ+06 and SDTL+06] that the RSSI between -90 and -80 dBm produces a PRR of approximately 90%.

The second investigates the effects of different RSSI settings for PRR and energy consumption. Apart from the maximum power settings, four additional RSSI settings are included. The minimum RSSI thresholds were set to -90, -80, -70 and -60 dBm whereas the corresponding maximum thresholds were -80, -70, -60 and -50dBm, respectively. The results demonstrate that there is an optimal region where lower power can be used whilst reliability is maintained at nearly 100%. The RSSI of over -80 dBm often provides the RSSI of nearly 100% and 50% of transmission energy is conserved.

An evaluation of clock drift is performed. Clock drift is important in the schedule-based approach. A sensor has an oscillator which generates timing signals in ticks. In this study, a 32-KHz clock is chosen and it provides 32,768 ticks per second. Clock drift occurs due to uncertainty in the ticking rate. Different local clocks may run at different speeds. The drift can be accumulated into a significant amount and time synchronisation is no longer maintained if it is not properly accommodated. The 20 ppm is suggested by the crystal oscillator data sheet [CMR200].

In the preliminary experiment, the sources send every 5 minutes, approximately every 10 million ticks. The base station monitored the time of data packet reception and calculated the drift. The measurements indicate that clock drift is hardware dependent and the maximum is less than 20 ppm. The same computational procedures were repeated and the results demonstrate that clock drift is also dependent upon the duration between two consecutive transmissions. It can be accurately predicted if its variation is monitored. Efficient scheduling algorithm can be thus established. The base station monitors the relative clock drift to each of the sources. Such measurements are broadcasted to the sources and they can adjust their scheduling locally to keep the idle listening period minimum. According to the measurements, up to 95% of the reserved duration and the corresponding idle listening energy can be conserved.

Chapter 7

Comparative Evaluation of PoRAP

An overview of three contention-based protocols, CSMA, S-MAC and B-MAC, is given in this chapter. An analysis of the parameter space of the three protocols and PoRAP is conducted to investigate how the key parameters affect energy consumption. As PoRAP suits low duty cycle applications, Great Duck Island, which is an important wireless sensor network application, is chosen as a comparative scenario. Its parameter settings are adopted and the evaluation methodology of energy consumption in B-MAC is extended. The average energy usage per second is calculated for each protocol and the results are compared to determine which protocol is able to conserve the most communication energy under the chosen scenario.

7.1 Overview

In the second half of this chapter a comparative evaluation of PoRAP is presented. The main objective of PoRAP development is to conserve energy so energy consumption is compared with three protocols for Wireless Sensor Networks (WSNs) that try to conserve energy consumption. These protocols adopt a multiple hop and random access approach. As such they may be deployed in a wider range of settings than PoRAP. This comparison focuses on environments where it is appropriate to use PoRAP. The three protocols are Carrier Sense Multiple Access (CSMA), Sensor Medium Access Control (S-MAC) and Berkeley MAC (B-MAC). Both B-MAC and S-MAC are specifically developed for low duty cycle applications and CSMA is the default MAC protocol in TinyOS. The parameter space of each protocol was analysed and the methodology used in [PHC04] adopted.

Communication accounts for a significant amount of energy consumption in WSNs. There are four important sources of energy wastage in a shared medium system; collision, overhearing, control packet overhead and idle listening [YHE03]. Some sources may transmit their data simultaneously and collisions may occur, resulting in collided data not reaching its destination. Data retransmission and corresponding energy is then required. Overhearing occurs when a node listens and receives the packets which are not destined for it. Reception energy is wasted as the node has to check whether it is the required destination. Control information is an important component of a network protocol designed to achieve a defined goal, but this information must be included in an additional packet and more energy is therefore consumed. Idle listening is another problem and the corresponding energy wastage increases with time. B-MAC and S-MAC solve this problem by periodically switching the nodes to sleep mode when they are not receiving data to conserve energy.

- B-MAC provides reliable data reception by preamble transmission. The preamble length must be at least a check interval which can be considered a sensing period in B-MAC. The preamble can be considered as a major overhead of the B-MAC protocol. A longer check interval or preamble results in higher energy consumption.

- In S-MAC, an active period is provided for communication setup which includes carrier sensing, hidden node avoidance and synchronisation between neighbours. The default duration is 115ms.

- The sources running CSMA are not switched to sleep mode. Hence, idle listening is the key source of energy wastage in CSMA.

- The number of sources directly relates to the control packet size in PoRAP. Prior to data transmissions, the sources receive the broadcast control message which can be considered as an overhead.

As PoRAP adopts the schedule-based approach, it is suitable for low duty cycle applications such as habitat and environmental monitoring systems. Each source has to wait for the others to complete their transmissions before sending again. There are several protocols particularly developed for such applications and PoRAP is compared to B-MAC, S-MAC and CSMA in terms of energy consumption. The analysis begins with a parameter space study to discover which attributes affect the energy conservation performance. Parameter settings in the Great Duck Island (GDI) are used for comparative study.

The GDI [MPS+02] is an important study of an environmental monitoring Wireless Sensor Network and was used to compare the protocols. The sampling period is 300s or 5 minutes and the data payload is 36 bytes [PHC04]. The chosen active duration for S-MAC is 115ms and the check interval is 10ms for B-MAC. The energy consumption required for transmitting a bit of data is used as a metric and allows an evaluation of how much energy each protocol would consume within the GDI scenario.

7.2 Overview of Compared Protocols

The energy consumption of PoRAP is compared to that of three existing protocols; Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), Sensor-MAC (S-MAC) and Berkeley-MAC (B-MAC). An overview of each protocol is given as follows:

7.2.1 Carrier Sense Multiple Access

CSMA with Collision Avoidance (CSMA/CA) is the default Medium Access Control (MAC) protocol in TinyOS, an open-source operating system for wireless sensor networks used in this dissertation. In CSMA, the source senses the shared medium for any ongoing transmission prior to initiating its own transmission. If the channel is declared free, the packet will be transmitted. However, the source has to wait or backoff until the channel is free.

There are two approaches proposed in the case of a busy channel [KT75]. Firstly, the source reschedules the retransmission of the packet with respect to the retransmission delay distribution. When the backoff time ends, the source conducts the carrier sensing processes again. This scheme is named "non-persistent CSMA". The random delay may be applied prior to transmissions in order to avoid collision when some sources have the same schedule.

Another scheme is "p-persistent CSMA" where the source transmits its packet with probability, p, after the channel has become free. Therefore, the source has to keep sensing during the ongoing transmission. In the special case where $p = 1$, or 1-persistent, the source transmits its packet immediately after the channel is free. The immediate transmission may result in high channel usage. However, there may be a case where two or more sources are listening to the channel and waiting to transmit at the same time. Collisions are likely to occur. Non-persistent CSMA can be seen as 0-persistent scheme.

In order to accommodate the trade-off between non- and 1-persistent, a value of p between 0 and 1, is selected. When the channel is free, the source delays its transmission with the probability of $(1-p)$ by a specific interval or slot size. Therefore, the sources have different transmission schedules with respect to the slot size.

Collision avoidance has been introduced to the CSMA and is named "CSMA/CA". The main concept is to defer both channel access and transmission. An additional period, Distributed Interframe Space (DIFS), is used. The Interframe Space (IFS) intervals can be seen like a guard used to avoid overlapping between the frames. The DIFS is equal to the shortest IFS (SIFS) plus one or two slot times [Erg02]. Like CSMA, the source senses the channel before transmitting. It immediately sends the packet if the channel is detected free. Otherwise, it has to wait for an additional DIFS period after the current transmission is finished. The waiting source selects a random number of slots between the minimum and maximum contention window (CW). This number is also used as an initial value for the backoff counter. The summation of DIFS and random number of slots is the deferred channel access duration.

The waiting source senses the channel again after the deferred access interval has ended. If there are additional transmissions conducted by other nodes, the waiting source freezes its counter. Otherwise, the counter is decremented. The waiting source resumes decrementing its counter after the nodes have finished their transmissions and a DIFS interval. The source can access the channel and send only when its counter has reached zero.

Medium sensing is crucial in CSMA to investigate whether the medium is free. All sources must backoff to avoid synchronizing their communication. Either fixed or random backoff may be applied if the source has data to send and the channel has been declared free [WC01]. Another backoff is used if ongoing activities are detected in the channel to avoid data collisions. Data collision may be avoided as there should be only one node using the medium for transmission. However, hidden node problems can occur when two nodes located outside the communication range of each other send data to a third node within the ranges of the transmitting nodes at the same time. Collisions thus occur at the receiving node and energy is wasted.

Nodes are not switched to sleep mode in CSMA. They have to listen to all incoming signals and receive all packets even if they are not the destination. Therefore, overhearing is not accommodated and a significant amount of idle listening energy is wasted. Both medium sensing and backoff can be determined as a control mechanism in CSMA. The nodes are also in listening mode when they sense the medium. It can be concluded that listening energy accounts for the most significant amount of energy in CSMA when the data reporting rate is low.

7.2.2 Sensor-MAC

Sensor-MAC (S-MAC) is a MAC protocol for multi-hop wireless sensor networks (WSNs). Prolonging sensor lifetime and supporting scalability and adaptivity to network changes are the main goals of S-MAC development. Several sources of energy wastage include collision, overhearing, control packet overhead and idle listening. Unlike the IEEE 802.11 which is primarily concerned with bandwidth utilisation, S-MAC proposes a low duty cycle to be the default mode of sensor operation. S-MAC has three key assumptions. Firstly, WSNs are multi-hop. A large number of sensors can benefit from short-range and multi-hop communications to conserve energy. Secondly, in-network processing is critical to WSN lifetime. Traffic reduction may decrease communication power but it may increase overall latency. Finally, S-MAC assumes that WSN applications will have long idle periods and be able to tolerate some latency. S-MAC adopts the Request To Send / Clear To Send (RTS/CTS) mechanism to avoid collisions caused by the hidden node problem.

Each sensor sleeps for some time and wakes up to listen to the medium for possible data reception. The radio is switched off during sleep and a timer is used for wake up. The sleep interval can be changed depending on different applications which may require different duty cycles. The node can choose its own listen/sleep schedule. As S-MAC supports a multi-hop network, synchronisation between neighbours is required. Sensors exchange their schedules by periodically broadcasting a synchronisation period (SYNC) containing the sender's address and the time of its next sleep to their intermediate neighbours. Sensors have to coordinate their sleep schedules rather than randomly sleep on their own. Each sensor maintains a schedule table which stores the schedules of its neighbours. Several policies in setting and updating the table entries are provided. Therefore, neighbour discovery is required and should not be performed too often due to energy concerns. In order to maintain synchronisation, S-MAC uses a relative timestamp and the listen period is significantly longer than the clock error or drift.

S-MAC also proposes an adaptive listening approach to support heavy traffic where delay may be important. The concept of adaptive listening is to switch the sensor from the low-duty-cycle to a more active mode. S-MAC lets the sensor which overhears transmissions of its neighbours wake up for a short period of time at the end of transmission. This mechanism therefore allows the neighbour to pass the data to the switched sensor immediately without waiting for its scheduled listening time. S-MAC takes carrier sense, transmission and sleep delay into consideration. Several equations were derived for calculating latency [YHE03].

In order to avoid overhearing, S-MAC suggests that all the immediate neighbours of both sender and receiver should sleep after they hear the RTS or CTS packet until the current transmission is finished. S-MAC also provides message fragmentation capability. A long message will be fragmented into many small pieces and they will be transmitted in a burst. One RTS and one CTS frame are required for all fragments. If the sender does not receive the ACK of a fragment, it will extend the reserved transmission time for one more fragment. The current fragment will also be retransmitted immediately. S-MAC has been implemented on both Rene and Mica motes for evaluation.

Like CSMA, medium sensing is conducted prior to data transmission. Time synchronisation results in three main advantages. Firstly, data collisions due to the hidden node problem can be avoided and overhearing can be minimised further. Secondly, the node and its neighbours exchange their schedules so they know when they should wake up for data communications. Lastly, they are in sleep mode more often and idle listening can be minimised. In order to achieve this, additional data exchanges and corresponding energy are required. More control energy is thus consumed.

7.2.3 Berkeley MAC

Berkeley MAC (B-MAC) is a carrier sense media access protocol for wireless sensor networks (WSNs). Its design is motivated by the Great Duck Island (GDI) scenario and is based upon a 1% duty cycle. B-MAC supports collision avoidance, reliable data delivery and power conservation. It also provides bidirectional interfaces for system services such as application modules to optimise performances such as throughput, latency or power conservation. The interfaces allow network services to adjust B-MAC. Three key capabilities of B-MAC are given in the following paragraphs.

In order to achieve collision avoidance, B-MAC uses Clear Channel Assessment (CCA) to detect ongoing transmissions. Bigger variations in signal strength occur when there is no transmission because of outliers. Frame reception is indicated by higher and more stable signal strength. Prior to transmission, the noise floor is estimated using software automatic gain control. Channel samplings are taken when the channel is assumed to be free; such as immediately after transmission or data not being received by the radio. The received signal strength is then monitored. However, this may lead to false negatives. B-MAC detects outliers to check the channel availability. The channel is declared clear if an outlier is found. Conversely, ongoing transmissions are indicated if five samples are taken and no outlier is found.

For reliability support, B-MAC provides optional link layer acknowledgement support. The data receiving interval is related to the manipulated duty cycles. The periodic channel sampling is called the Low Power Listening (LPL). The sleeping duration after the sensor wakes up or receives data depends upon the CCA results. The idle listening time should be long enough to receive data successfully. If no packet is received within a predefined timeout, the node is switched back to sleeping mode. The preamble length must be at least as long as the sampling period. The interval between LPL samples should be maximised in order to minimise the sampling interval. At present, some of the B-MAC primitives including CCA, duty cycle and sleep interval settings have been implemented in TinyOS.

Medium sensing prior to data transmission is also conducted in B-MAC by applying CCA. Like CSMA, a hidden node problem may occur in B-MAC and energy is wasted on collided data transmissions. Overhearing is not accommodated as there is no synchronisation between the neighbours. The nodes periodically wake up to check the incoming signal during the check interval. There may be a case where there is no packet being sent to the node. Idle listening is minimised as the nodes are switched to sleep mode if no packet is received within the timeout. The mechanism provided to achieve reliable data reception can be considered as control aspect. Preamble transmission and reception is the main overhead in B-MAC. The preamble length must be at least the check interval. A longer preamble length means that more communication energy is consumed.

7.2.4 Summary

B-MAC and S-MAC are developed to support low duty cycle applications. They assume a low sampling period of the sources. Additional mechanisms are added prior to data delivery. For example, a preamble is transmitted and received to provide reliable data reception in B-MAC. The active period is used for carrier sensing, hidden node avoidance and synchronisation in S-MAC. Such mechanisms can be considered as protocol overheads which significantly affect the energy consumption. CSMA is a traditional contention-based MAC protocol. It provides collision avoidance (CA) by sensing the medium prior to transmission. However, it does not prevent hidden node problem.

Unlike CSMA, S-MAC and B-MAC, PoRAP adopts the schedule-based approach where carrier sensing prior to data transmission is not applied. A time slot is allocated for each source so data transmission is conducted within the slot and data collision is avoided. Other sources can be in sleep mode during data transmission and idle listening is minimised. Moreover, only one source sends at a time and therefore the hidden node problem is also avoided. However, control packet broadcast is required for signaling transmission power adaptation and time synchronisation and is an overhead in PoRAP. The length of a control packet is dependent upon the number of sources.

7.3 Methodology

This chapter focuses on analysis of energy consumption of CSMA, S-MAC, B-MAC and PoRAP. Each of them has a different set of operations required to achieve the energy conservation goal. Prior to comparing the energy consumption, a study on the parameter space is conducted in order to investigate how each parameter affects the energy usage. Several parameter settings specified in the production habitat monitoring system, Great Duck Island (GDI), along with [PHC04] are used for the comparison.

7.3.1 Great Duck Island

PoRAP is specifically developed for low duty cycle and periodic based applications such as habitat and environmental monitoring systems. Great Duck Island (GDI) is an important production WSN application. This section aims to provide core details of the GDI project [MPS+02].

GDI is a habitat WSN application. It is located 15km south of Mount Desert Island, Maine and it covers an area of 237 acres or approximately 959,105m^2. Tiered architecture was used; the first tier consisted of sensor patches and gateways. There were up to 100 sensors in each patch. The gateway acted as a relay node. Data communication within each patch was either single or multi-hop depending on the distances between sensors and their gateway. The second tier provided connectivity between multiple patches.

The motes remained at their original positions throughout a 9 month operation. The numbers of motes increased from 32 in November 2002 to 190 in August 2003. There were two main types of sensors including weather and burrow and several physical data such as temperature, humidity and pressure were collected by the motes. The selected sampling period in GDI was 5 minutes or 300s [MPS+02]. The same period was used in the Redwoods environmental monitoring system [TPS+05]. The data payload was 36 bytes and the required duty cycle was approximately 1.7%. [PHC04]. Several parameter settings in GDI and those given in [PHC04] are used in this comparative study. Energy consumption required by each protocol is calculated and compared to the GDI scenario.

7.3.2 Calculation of energy consumption

In order to determine the effects of parameter space, the methodology given in [PHC04] is adopted. The chosen metric is average energy usage per second. It is defined as a ratio of total energy consumed by a source to the total number of transmitted data bits in 1 second. The total amount of energy consumption is the summation of energy used for control packet reception, data packet transmission, listening and sleeping. The data payload is used for calculating the total number of sent bits.

According to the methodology, communication delays required for a specific size of data payload is calculated with respect to a 1-second interval by taking the sampling period into consideration. The sampling period is defined as an interval in seconds between two data collections and transmissions. The inverse of the sampling period indicates the amount of data being collected and transmitted within a second or the data reporting rate. For example, a 10 second sampling period means that a source sends one piece of 36 byte data every 10 seconds. Alternatively, it can also be stated that, on average, the source sends 3.6 bytes of data every second.

There are four communication modes including sending, receiving, listening and sleeping except in CSMA where the nodes do not sleep. An interval for each communication mode is computed based upon the 1-second interval. The required energy is the product of the communication interval and the relevant power. As the communication protocol in [PHC04] was developed for multi-hop sensor networks, each node located within the communication range of the sending node has to receive the transmitted packets and the number of neighbours is included in the calculation of reception energy. The duration computations are detailed as follows:

- **Transmission**: The duration required for data transmission per second is equal to the product of the data reporting rate, which is dependent upon application’s requirement in packets per second, the number of bytes being transmitted and the duration required for transmitting 1 byte of data.

- **Reception**: The receiving duration is equal to the products of the attributes used in the transmission and the number of neighbours. Hence, each source has to receive all of the incoming messages from its neighbours.

- **Listening**: The listening period is equal to the product of total durations required for wakeup and carrier sensing in CSMA, B-MAC and also synchronisation between nodes in S-MAC. The wakeup interval is obtained from [Lim06] where the measurements were conducted directly from Tmote Sky motes. In total 4.18ms was required for starting the radio voltage regulator (0.76ms), starting the radio oscillator (1.84ms), preparing the packet (0.12ms), loading the radio FIFO (1.1ms) and setting the radio to transmission mode (1.02ms).

- **Sleeping**: The sleeping period is the average time per second after subtracting transmission, reception and listening.

After obtaining all communication durations, they will be multiplied by the power in milli-watts (mW) to get energy consumption. According to [Tmote], the required power for data transmission depends upon the power settings. For example, the power of 25.50 and 52.20 mW are used at the minimum and maximum settings. The required power for receiving, listening and sleeping is respectively 59.10, 1.10 and 0.06 mW. The selected data payload size is set to 36 bytes. The number of neighbours ranges from 1 to 100 nodes. The data sampling periods of 10, 50, 100 and 300s are used in the parameter space study. Section 7.4 illustrates the parameters which are required for computing the energy consumption.

7.4 Analysis of Parameter Space of Protocols and Comparative Study

The main objective of parameter space analysis is to investigate how each parameter affects the energy consumption. Several attributes required for the calculation are previously provided in Section 7.3.2. As each protocol has its own set of different message exchanges, the details of communication delay calculations are described separately.

Apart from comparing the energy consumption between protocols, the idle listening periods required by B-MAC and PoRAP are also compared. In the case of PoRAP, the results shown in Table 6.8 demonstrate the reserved duration for clock drift used whilst the duration required by B-MAC is computed based upon the 10ms check interval.

7.4.1 Analysis of parameter space

A) B-MAC

The driving force of B-MAC development is to support low duty cycle communication in environmental monitoring systems such as Great Duck Island (GDI) [MPS+02] and Redwoods [TPS+05]. The sensors in GDI operated at approximately 1.7% duty cycle. After physical data collection and transmission, the sensors were in sleep mode for 5 minutes.

Three main parameters affecting the energy consumption include the check interval, the data sampling period and the number of neighbours. The check interval indicates the duration of the source listening to the incoming signal. An inverse of the check interval is therefore the channel sampling frequency. B-MAC provides reliable data reception by preamble transmission. The preamble length must be at least the check interval. The size of preamble must be included in the total number of sent and received bytes.

The data sampling period illustrates the duration between two consecutive data collections and transmissions and its inverse indicates the data reporting rate in packets per second. The number of neighbours is important to the calculation of reception duration as all nodes located within the communication range of the sending node have to receive the message.

Parameter settings

The settings in [PHC04] apply in this analysis such as data payload size and the check intervals of 10, 20, 50, 100 and 200ms.

Results

Table 7.1 shows the effects of varying the data sampling period and the check interval on the energy consumption of different numbers of neighbours. The energy consumption is averaged from the cases of 1 to 100 neighbours.

Several observations can be made out of Table 7.1 as follows:

1. At specific sample periods and check intervals, a higher communication energy is required by each source for transmitting one bit of data if it has more neighbours. The source has to receive and forward the messages which are transmitted by all neighbours.

2. The source uses less energy if the data is sampled less often. The number of transmissions and receptions and the corresponding energy consumption decrease in longer sampling

periods. A significant reduction in energy consumption is observed if the sources sample every 50s or longer, especially at higher number of sources.

3. Energy consumption often increases with the check interval, especially with a high number of neighbours. A longer preamble is required if the check interval increases or the source performs channel sensing less often. Preamble transmission and reception energy increase with the check interval whilst the listening energy is less. The power required by transmission and reception is significantly higher than that of listening. A higher total energy is then consumed.

4. There are some cases where lower energy is consumed even if the check interval is longer, especially at a lower number of neighbours. For example, at a 300s sampling period, 2.12 and 1.72 x 10^{-3} mJ are consumed at 10ms and 20ms check intervals, respectively. In these cases, the listening energy accounts for the largest proportion of total energy usage. The sources listen for longer periods at shorter check intervals and more energy is consumed.

Table 7.1: Effects of data sampling period and check interval on energy consumption in B-MAC

Sampling Period (s)	Check Interval (ms)	Energy Consumption (x10^{-3} mJ)		
		1 neighbour	Average	100 neighbours
10	10	2.06	14.05	26.04
	20	1.06	23.73	45.86
	50	2.03	54.58	107.14
	100	3.34	106.66	209.98
	200	6.20	211.04	415.97
50	10	1.78	4.18	6.58
	20	1.09	5.51	9.94
	50	0.81	11.32	21.83
	100	0.96	21.62	42.28
	200	1.47	42.42	83.38
100	10	1.75	2.94	4.14
	20	1.02	3.24	5.45
	50	0.66	5.92	11.17
	100	0.66	10.99	21.32
	200	0.88	21.35	41.83
300	10	1.72	2.12	2.52
	20	0.98	1.72	2.46
	50	0.56	2.31	4.06
	100	0.46	3.90	7.35
	200	0.48	7.31	14.13

In order to determine the effects of parameters on the energy consumption, curve fitting is applied to the data shown in Table 7.1. The selected technique is the R-square value which reflects the ratio of raw data that can be fitted. The average energy consumption of up to 100 neighbours is used. Figure 7.1 shows the curve fittings of the relationships between check interval and average energy usage at various sampling periods. The relationships between sampling period and energy consumption are demonstrated in Figure 7.2.

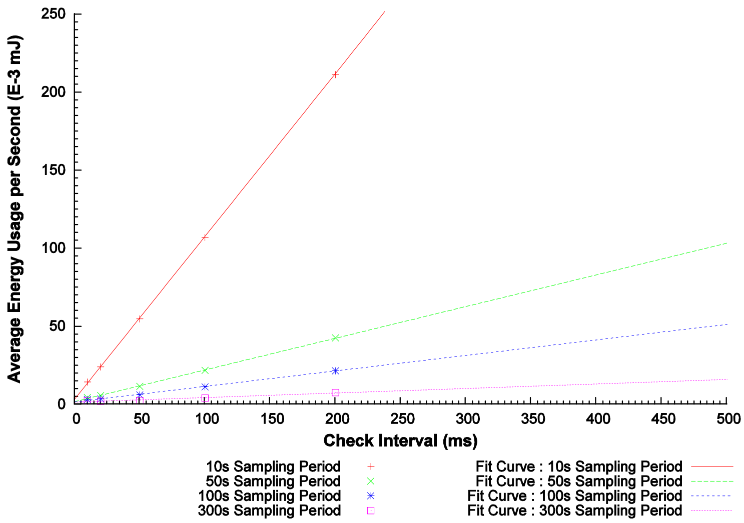


Figure 7.1: Curve fittings of average energy usage in B-MAC at various check intervals

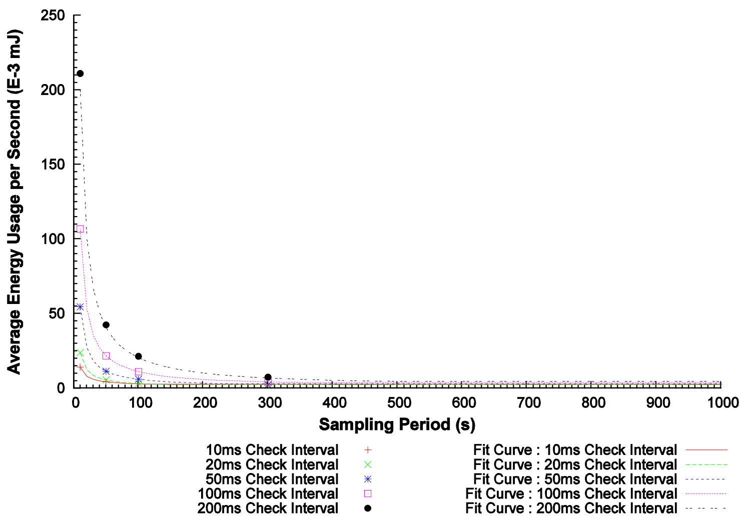


Figure 7.2: Curve fittings of average energy usage in B-MAC at various sampling periods

Linear relationships are observed in Figure 7.1 whilst inverse relationships are used in the plots in Figure 7.2. The R-square values for both figures are over 0.99 or more than 99% of data can fit. A smaller amount of energy will be used if a shorter check interval is used. However, the shortest duration is 4.18ms as it is required for starting and initialising the hardware components [Lim06].

More energy is required for a longer check interval if a sampling period is fixed. However, less energy is consumed if the sensors sample the data less frequently. A significant reduction in energy is observed when the sampling period is decreased from 10 to 100 seconds. The degree of reduction is lower when a shorter check interval is used. For example, at a 200ms check interval, almost 10 times the energy is consumed if a sampling period of 100s is used instead of 10s whilst approximately 3 times the energy is saved at a 10ms check interval.

In summary, the data sampling rate and check interval affects the transmission and reception energy. The number of neighbours is included in order to compute the reception duration and corresponding energy. Preamble transmission and reception can be considered as an overhead in B-MAC and it increases with the number of neighbours. The source transmits its data to all of its neighbours located within the communication range. Each neighbour has to listen and receive their data. Routing is also conducted in order to forward the data to its destination. The cost in terms of energy consumption is added to both sender and receiver to provide a reliable data reception at the receiver. The receiver's wakeup schedule also affects the energy consumption.

B) S-MAC

Like B-MAC, S-MAC is also a contention-based protocol specifically developed for multi-hop wireless sensor networks. Additional frames are required for synchronisation and hidden node problem avoidance. A source exchanges its schedule by sending a SYNC frame to the neighbours. Traditional RTS/CTS handshake is adopted in order to avoid collisions caused by transmissions from nodes which are not located within each other's ranges. The ACK frame is also used for data reception acknowledgement. Transmissions and receptions of additional control frames affect the energy consumption.

The effects of the three main parameters; active duration, data reporting rate and number of neighbours on energy consumption per bit of data are studied. According to [YHE03], the default active period is set to 115ms. Carrier sensing, frame transmissions and receptions occur within this period. Energy consumption is equal to the product of communication delay and power. The data reporting rate is required to compute the number of packets per second. The data reporting rate is the inverse of the data sampling rate per second.

Parameter settings

Several settings in [YHE03] and [MG08] apply in this analysis. The lengths of SYNC, RTS, CTS and ACK are set to 8, 20, 14 and 14 bytes, respectively. The active intervals of 115, 250, 500, 750 and 1,000ms are used.

Results

Table 7.2 shows the effects of varying the data sampling period and the active interval on the energy consumption of different numbers of neighbours. The energy consumption is averaged from the cases of 1 to 100 neighbours.

Table 7.2: Effects of data sampling period and active interval on energy consumption in S-MAC

Sampling Period (s)	Active Interval (ms)	Energy Consumption ($x10^{-3}$ mJ)		
		1 neighbour	Average	100 neighbours
10	115	0.75	5.84	10.94
	250	1.24	6.33	11.42
	500	2.13	7.23	12.32
	750	3.03	8.13	13.22
	1,000	3.93	9.03	14.12
50	115	0.65	1.67	2.69
	250	1.13	2.15	3.17
	500	2.03	3.05	4.07
	750	2.93	3.95	4.97
	1,000	3.83	4.85	5.87
100	115	0.63	1.14	1.65
	250	1.12	1.63	2.14
	500	2.02	2.53	3.04
	750	2.92	3.43	3.94
	1,000	3.82	4.32	4.83
300	115	0.63	0.80	0.97
	250	1.11	1.28	1.45
	500	2.01	2.18	2.35
	750	2.91	3.08	3.25
	1,000	3.81	3.98	4.15

According to Table 7.2, several observations can be addressed as follows:

1. A source requires more energy to transmit a bit of data if it has many neighbours. The source has to receive and send more control frames and data from and to its neighbours. The total energy consumption therefore increases.

2. Greater energy consumption due to additional listening energy is required if the source listens for longer. The active interval reflects the listening period. The 1,000ms active duration demonstrates the 100% duty cycle when the source is never switched to sleep mode.

3. Less energy is consumed if the source samples the data less frequently. Both the number of transmitted and received bytes per second and the corresponding energy decreases with a longer data sampling period.

Curve estimations are conducted on the results in Table 7.2 in order to study the effects of the factors on an extended set of values. A suitable fitting technique is the R-square value. Figure 7.3 shows the curve fitting of the relationships between the active interval and the average energy usage at various sampling periods. The average energy consumption of up to 100 neighbours is used. The relationship between the sampling period and energy consumption are illustrated in Figure 7.4.

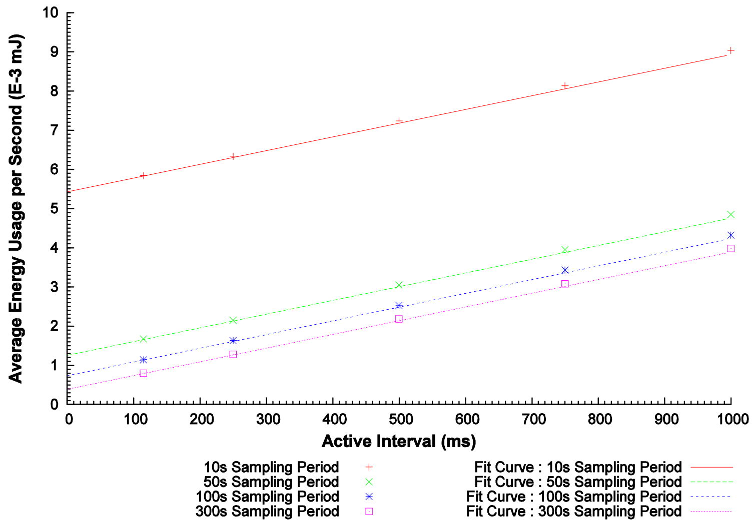


Figure 7.3: Curve fittings of average energy usage in S-MAC at various active intervals

At a specific sampling period, the average energy usage per second linearly increases with the active interval. Lower energy consumption is obtained by using a shorter active interval. However, the default duration is 115ms [YHE03]. A lower active interval cannot accommodate the transmission and reception delays when there are many neighbours.

A considerable reduction in energy usage is observed at longer sampling periods. Up to 10 times the energy can be saved if the sensors sample every 300s instead of 10s. Figure 7.4 demonstrates an inverse technique used for fitting the plots of the relationship between the sampling period and energy usage. A significant reduction in energy consumption will be obtained if the sensors sample every 100s or longer. The main reason is that the sensor can be in sleep mode longer. The R-square values are over 0.99.

In summary, several control frames including SYNC, RTS, CTS and ACK frames can be considered as overheads in S-MAC. The number of control transmissions and receptions increases with the number of neighbours. The sending source exchanges its scheduling information with its neighbours. An RTS is sent if the source has data to send. The DATA frame is not delivered unless the source receives the CTS. The receiver sends the ACK frame after the DATA is received.

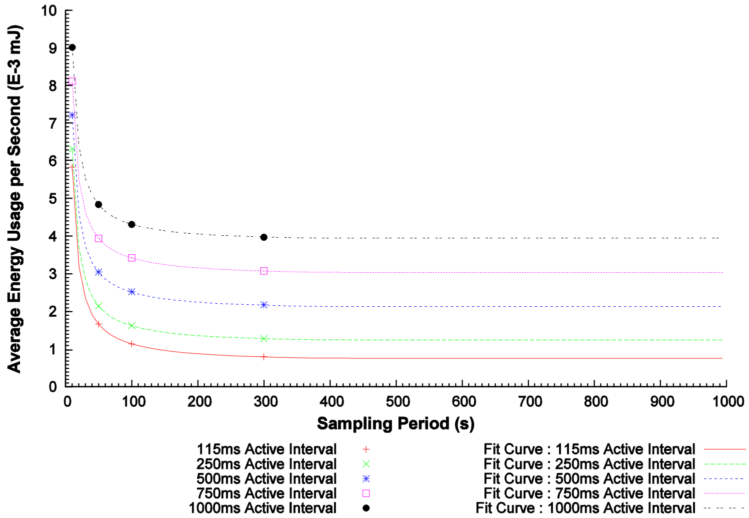


Figure 7.4: Curve fittings of average energy usage in S-MAC at various sampling periods

The minimum active duration is 115ms as specified in [YHE03]. In order to yield a low duty cycle, the data sample period should be high. For example, the sources sample data every 11.5s to achieve a 1% duty cycle. For a higher number of neighbours, the source which samples data more frequently requires a greater amount of energy consumption than the one with a longer sampling period.

C) CSMA/CA

Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is the default Medium Access Control (MAC) protocol in TinyOS. Prior to transmission, the source senses the medium in order to detect whether there are ongoing activities. As the sources listen all the time, the listening energy accounts for a large proportion of the total communication energy. The effects of the two main parameters including the data sampling period and the number of neighbours on energy consumption per bit of data are studied.

Parameter settings

The selected data payload size is 36 bytes and 4 application data sampling periods are used as in the B-MAC and S-MAC analyses.

Results

Table 7.3 shows the effects of varying the data sampling period on the energy consumption of different numbers of neighbours. The energy consumption is averaged from the cases of 1 to 100 neighbours.

Table 7.3: Effects of data sampling period on energy consumption in CSMA

Sampling Period (s)	Energy Consumption ($x10^{-3}$ mJ)		
	1 neighbour	Average	100 neighbours
10	3.85	5.62	7.39
50	3.81	4.17	4.52
100	3.81	3.98	4.16
300	3.80	3.86	3.92

Several observations can be made from Table 7.3 as follows:

1. At a specific sampling period, a source requires more energy to transmit a bit of data if the numbers of its neighbours increase. Also, the source has to receive more data packets from the neighbours. Hence, the total amount of energy consumption increases.

2. A small increase in energy consumption, due to an increasing number of neighbours, occurs at high sampling periods such as 300s. The main reason is that listening dominates the total energy consumption in CSMA. The effects become more significant when the sources sample more often.

3. The effects of the data sampling period on energy consumption are insignificant, especially when the number of sources is small. Therefore, high energy consumption in CSMA occurs when there are many sources in the network and they sample the channel more often.

The curve estimation of the results shown in Table 7.3 is shown in Figure 7.5. The average energy consumption of up to 100 neighbours is used.

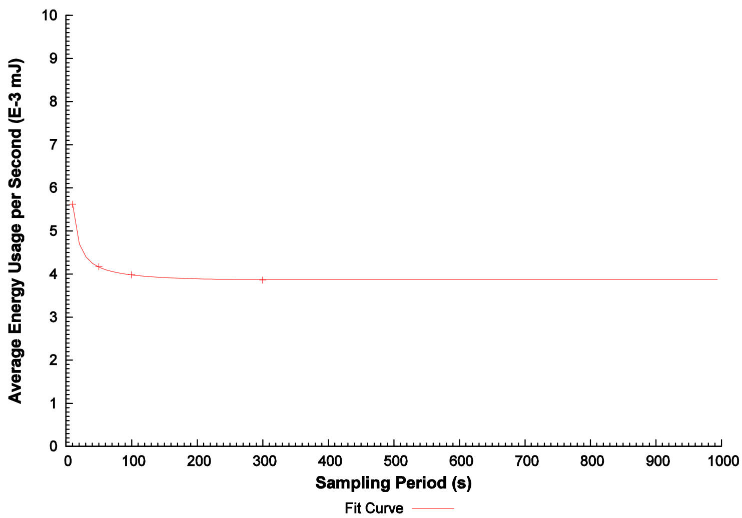


Figure 7.5: Curve fittings of average energy usage in CSMA

Like B-MAC and S-MAC, less frequent data sampling results in less energy usage. This is because there are fewer data communications within a specific interval. Approximately 4 milli-joules (mJ) is required if the sensors sample every 100ms or longer.

In summary, idle listening is an important overhead in the CSMA as the sources constantly listen to the signal. The sampling period and the number of neighbours affect the energy consumption. A high amount of energy is required when the network includes many sources and they sample the medium more often.

D) PoRAP

There are two main parameters in PoRAP. The control packet size is directly dependent upon the number of sources. A byte of payload is required in the control packet for notifying the transmission power adaptation to every four sources because two bits are required for signaling power adaptation to each source. The duration of the control packet reception and the corresponding energy requirement for the four sources is the same. The effects of sampling periods and number of sources on the energy consumption are considered in this section.

According to PoRAP design, the scheduling information takes 6 bytes in the control packet whilst a byte is used for notifying transmission power adaptation for every four sources. Several equations given in Section 5.5.4 can be used for slot length determination. The first data slot starts after the sources' application layer has completely received the control packet. This concept ensures that the whole control packet is received. Both scheduling and power adaptation information can be retrieved at the application layer. This information is used to calculate the schedule and adjust the power prior to transmission.

The selected numbers of sources are the same as in the previous analyses. The size of the control payload required for transmission power adaptation and time synchronization depends upon the number of sources. Table 7.4 demonstrates how sampling periods and number of sources affect the energy consumption per bit. As PoRAP is specifically designed for direct communication, the maximum power is always used in the analysis.

Table 7.4: Effects of data sampling period on energy consumption in PoRAP

Sampling Period (s)	Energy Consumption ($\times 10^{-3}$ mJ)		
	1 neighbour	Average	100 neighbours
10	0.27	0.27	0.28
50	0.22	0.22	0.22
100	0.21	0.21	0.22
300	0.21	0.21	0.21

Several observations can be made according to Table 7.4 as follows:

1. At a specific sampling period, a source requires more energy to transmit a bit of data if the numbers of its neighbours increase. The main reason is that the size of control packet increases with the number of sources.

2. At a particular number of sources, the energy consumption decreases with an increasing sampling period. The sources communicate with their base station more often if the sampling period is smaller.

3. Unlike the multi-hop protocols, the sources are not responsible for packet forwarding. They can be in sleep mode and consume less energy whilst the others are sending.

Figure 7.6 illustrates the curve fitting of the relationship between the sampling period and the average energy usage per second. The average energy consumption of up to 100 neighbours is used.

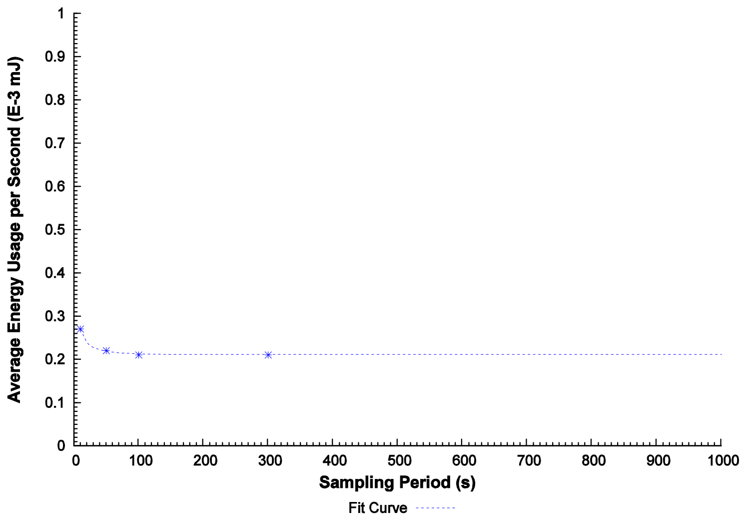


Figure 7.6: Curve fittings of average energy usage in PoRAP

A similar observation is obtained in Figure 7.6 compared to Figure 7.2, 7.4 and 7.5. A longer sampling period results in a lower average energy usage per second. The reduction in energy in PoRAP is the least compared to B-MAC, S-MAC and CSMA. This is because the packet is delivered directly to the base station and no data forwarding is required. The overhead is only related to the number of sources. However, PoRAP cannot accommodate a high frequency of transmission especially when there are many sources as it is a schedule-based protocol. It has to wait for all sources to complete their transmissions to start a new communication cycle.

In summary, control packet reception can be considered as an important overhead in PoRAP. The size of control packet is related to the number of sources. According to the parameter settings, a source consumes approximately 0.2 to 0.3 milli-joules (mJ) in transmitting one bit of data. Like other protocols, a higher amount of energy is required when there are more sources in the network and the sampling period is lower.

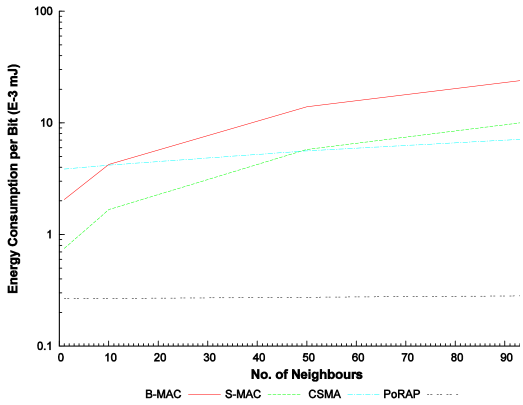
7.4.2 Comparative study

The previous section demonstrates analyses of the parameter spaces in B-MAC, S-MAC, CSMA and PoRAP. Several overheads are indicated and they affect the energy consumption of the source. For example, the check interval is an important attribute in B-MAC as it directly relates to the preamble length. A longer preamble transmission and reception result in a higher amount of energy usage. An active period is used in S-MAC for communication setup and synchronisation between neighbours. The source transmits, receives and listens to the signals delivered by its neighbours during this period. The sources are not switched to sleep mode in CSMA. Idle listening is therefore an important source of energy wastage in CSMA. Unlike the multi-hop protocols discussed, PoRAP supports direct communications in wireless sensor networks and is more power aware. The control packet is considered as an overhead and its size depends upon the number of sources.

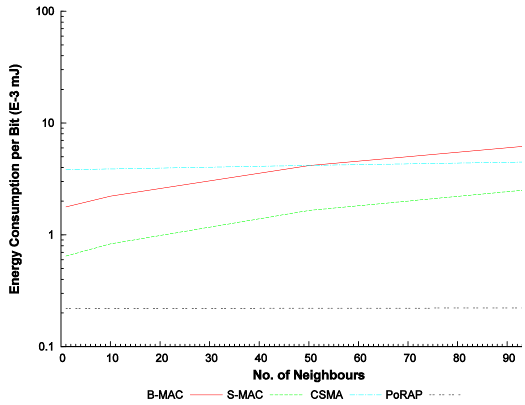
This section aims to compare the protocols' performances in terms of energy consumption based on the Great Duck Island (GDI) project. In GDI, the sources sent their data every 5 minutes, that is the sampling period was 300s. A data payload size of 36 bytes was used [PHC04]. PoRAP can be used in a demonstration consisting of sensing nodes and a base station. The selected numbers of sources are 1, 10, 50 and 100.

The chosen check interval for B-MAC is 10ms as it was used in [PHC04]. Moreover, it often uses the least amount of energy according to Table 7.1, especially at a higher number of neighbours. The selected active interval for S-MAC is 115ms as it is the default value according to [YHE03].

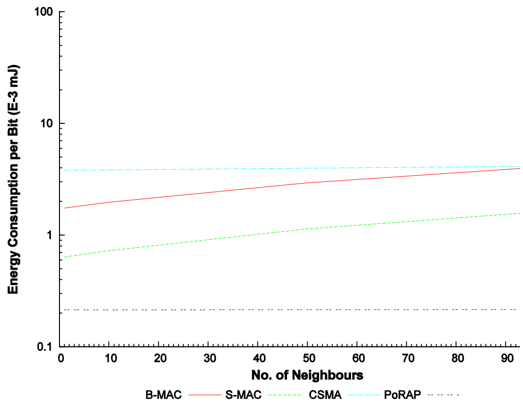
Figure 7.7 shows the comparison in energy consumption between B-MAC, S-MAC, CSMA and PoRAP. The sampling periods of 10, 50, 100 and 300s are used to indicate the differences in the results. Note that log scales are used to represent the energy consumption per bit.



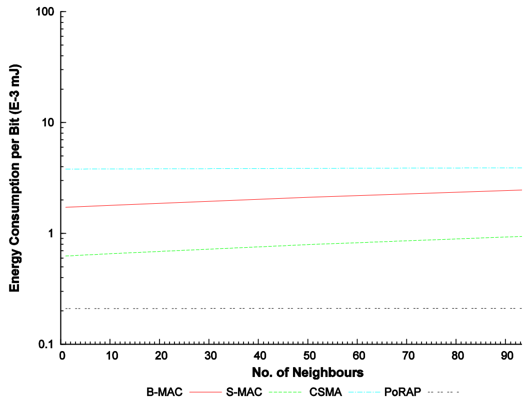
(a) 10s sampling period



(b) 50s sampling period



(c) 100s sampling period



(d) 300s sampling period

Figure 7.7: Comparison in energy consumption at various sampling periods

According to Figure 7.7, several observations can be made as follows:

1. In the case of B-MAC and S-MAC, the effects of the number of neighbours are greater than CSMA and PoRAP. The main reason is that both B-MAC and S-MAC have significant overheads such as preamble and control frame transmissions and receptions. However, idle listening is an important source of energy wastage in CSMA where the additional energy required for data communication is insignificant compared to the idle listening cost. As PoRAP is developed for direct communication, an increase in the number of sources results in a larger control packet. Larger packet reception consumes less energy compared to multiple packet receptions.

2. A longer sampling period results in less energy consumption as data communications occur less frequently. At 100s and 300s sampling periods, CSMA consumes the greatest amount of energy. S-MAC uses less energy than B-MAC as long preamble transmission and reception are required in B-MAC. CSMA outperforms B-MAC and S-MAC when the sources sample every 10s.

3. The chosen check interval for B-MAC and the active period for S-MAC are 10ms and 115ms, respectively. B-MAC is developed for low duty cycle applications where the high proportion of data communication costs is at the senders. Its main objective is to achieve the targeted lifetime. Reliable data reception is provided by means of preamble delivery. S-MAC avoids the hidden node problem by using an RTS/CTS handshake. Schedules are also exchanged between neighbours. A longer preamble and active period require more communication and listening energy.

4. PoRAP consumes the least amount of energy. The main reason is that it adopts the schedule-based approach where multiple transmissions and receptions are not required for data forwarding. Data is transmitted when the allocated slot arrives and it is delivered directly to the base station. Approximately 0.2 to 0.3 x 10^{-3} mJ of energy is consumed per bit of data. PoRAP conserves more energy when the sampling period is smaller and the number of sources is higher. For example, at the 300s sampling period and 50 sources, PoRAP consumes approximately 33%, 10% and 5% of that required by S-MAC, B-MAC and CSMA, respectively.

The amount of saved energy by PoRAP due to amendments in check interval and active interval settings in B-MAC and S-MAC are shown in Table 7.5 and 7.6, respectively. The selected sampling period is 300s. The average energy consumption is computed based upon the number of sources varying from 1 to 100 nodes.

Table 7.5: Comparison of energy consumption between B-MAC and PoRAP

B-MAC		Average Energy Consumption by PoRAP (x10^{-3} mJ)	Saved Energy by PoRAP (times)
Check Interval (ms)	Average Energy Consumption (x10^{-3} mJ)		
10	2.12	0.21	9.1
20	1.72		7.2
50	2.31		10.0
100	3.90		17.6
200	7.31		33.8

Table 7.6: Comparison of energy consumption between S-MAC and PoRAP

S-MAC		Average Energy Consumption by PoRAP (x10^{-3} mJ)	Saved Energy by PoRAP (times)
Active Interval (ms)	Average Energy Consumption (x10^{-3} mJ)		
115	0.80	0.21	2.8
250	1.28		5.1
500	2.18		9.4
750	3.08		13.7
1,000	3.98		18.0

Increases in the amount of conserved energy by PoRAP are observed in both Table 7.5 and 7.6 when check and active intervals are increased. The greater energy consumed by longer preamble communications in B-MAC and listening periods results in higher energy conserved by PoRAP.

The comparisons conducted in Table 7.5, 7.6 and Figure 7.7 are based upon the parameter settings with respect to the GDI scenario where the frequency of data transmission is low. PoRAP is specifically developed for the low duty cycle applications such as habitat and environmental monitoring WSNs. In order to investigate whether PoRAP is applicable to applications which require a high frequency of transmission, an experiment using one source is performed to determine the minimum sampling period to which PoRAP is applicable.

Table 7.7 compares the average energy usage per second of all protocols. The chosen check interval for B-MAC and active period for S-MAC are 10ms and 115ms, respectively. Figure 7.8 depicts the results shown in Table 7.7.

Table 7.7: Comparison of energy consumption at various sampling periods

Sampling Period (s)	Average Energy Usage per Second ($x10^{-3}$ mJ)			
	B-MAC	S-MAC	CSMA	PoRAP
0.1	36.37	13.58	8.87	5.96
0.2	19.04	7.10	6.34	3.08
0.5	8.64	3.21	4.82	1.36
1	5.18	1.92	4.31	0.78
2	3.44	1.27	4.06	0.50
3	2.87	1.05	3.97	0.40
4	2.58	0.95	3.93	0.35
5	2.40	0.88	3.90	0.32
6	2.29	0.84	3.89	0.30
7	2.21	0.81	3.87	0.29
8	2.14	0.78	3.87	0.28
9	2.10	0.77	3.86	0.27
10	2.06	0.75	3.85	0.27
20	1.88	0.69	3.83	0.24
50	1.78	0.65	3.81	0.22
100	1.75	0.63	3.81	0.21
300	1.72	0.63	3.80	0.21
500	1.72	0.62	3.80	0.21
1,000	1.72	0.62	3.80	0.21

According to Table 7.7 and Figure 7.8, PoRAP is capable of supporting high frequency transmission. The main reason is that a time slot is allocated to a source so it can transmit again without waiting. The CSMA consumes higher energy than B-MAC and S-MAC when the sampling period is longer than 1.5s and 0.25s, respectively. In the case where a source sends every 0.1s, PoRAP uses 16%, 44% and 67% of the energy of B-MAC, S-MAC and CSMA, respectively. Less energy is consumed by PoRAP at longer periods up to 300s which was used by [MPS+02] and [PHC04]. At the 1,000s sampling interval, PoRAP consumes 12%, 34% and 5.5% of the energy used by B-MAC, S-MAC and CSMA.

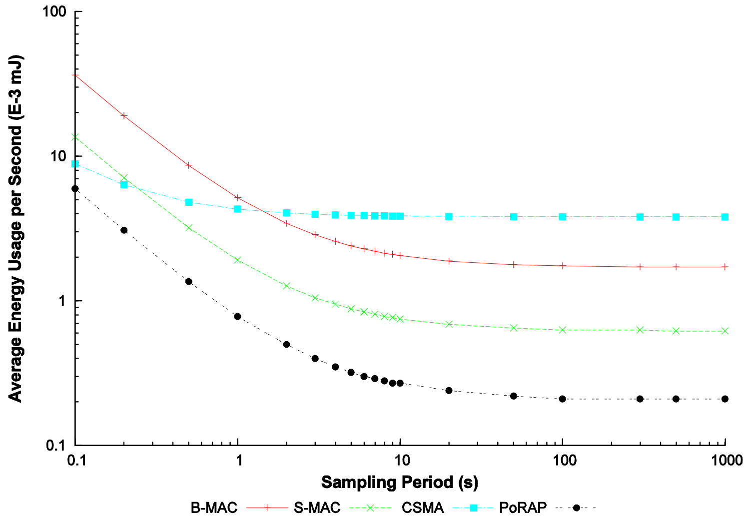


Figure 7.8: Effects of sampling periods on average energy usage per second

Previous results are based upon the assumption that the number of sources is known as the number of slots is equal to that of sources. However, there may be a case where the number of sources is unknown on advance. Further, the topology may be changed as some sources may leave or new sources may join the network. In such cases, the number of slots is higher than the number of sources. PoRAP is sometimes not applicable, for high duty cycle applications, as the source has to wait for the other slots to complete until the next communication cycle is started. Table 7.8 demonstrates the effects of the percentage of slot usage on minimum applicable sampling periods and corresponding average energy consumption in PoRAP. There is a single source in the network.

Table 7.8: Effects of percentage of slot usage on minimum applicable sampling period

Number of Allocated Slots	Slot Usage (%)	Minimum Applicable Sampling Period (s)	Average Energy Usage per Second ($x10^{-3}$ mJ)
100	1	3	0.40
50	2	1.5	0.59
20	5	0.6	1.17
10	10	0.3	2.12
5	20	0.2	3.08
2	50	0.1	5.96
1	100	0.1	5.96

A low duty cycle application is more efficient using PoRAP when the percentage of slot usage is high. However, PoRAP is not applicable if a source has to wait longer until the next cycle is started. Hence, a limitation of PoRAP arises when there is a high slot overhead because there are many sources in the network. Unlike PoRAP, the other protocols are applicable as they do not require slot allocations. At 20% of slot usage, PoRAP is not applicable at the 0.1s sampling period.

PoRAP applies when the source sends 5 packets every second (a 0.2s sampling period) as it uses 16%, 43% and 48.5% of the energy of B-MAC, S-MAC and CSMA, respectively. A significant amount of energy can be saved by PoRAP when it is applicable.

In summary, several parameter settings such as data payload size and sampling interval in the Great Duck Island [MPS+02] and those in [PHC04] are used in this comparative study. Longer communication durations result in a higher energy consumption. PoRAP is not significantly affected by the number of sources compared to S-MAC and B-MAC as intermediate nodes are not required for data forwarding. The main limitation of PoRAP is that it is not applicable to high duty cycle applications when the percentage of slot usage is low. However, it can conserve more energy than the other protocols when it can be used. The main reason is that it does not require multiple transmissions and receptions. Further, the sources are periodically switched to sleep mode to conserve energy.

Apart from considering energy consumption per bit per second, idle listening is an important source of energy wastage. CSMA uses the most amount of energy on idle listening, especially when the sampling period is high. Preamble is used in B-MAC for reliable data reception and its length is at least a check interval. Idle listening energy becomes significant for B-MAC for longer check intervals. Further comparison of required idle listening periods between B-MAC and PoRAP can be determined from Table 6.8 which demonstrates the minimisation of the listening period in order to maintain time synchronisation in PoRAP.

According to Table 6.8, four durations between two consecutive data transmissions are included. A 1s period is and 10ms check interval in B-MAC are used. This means that B-MAC has to conduct preamble communication for 10ms every second. Hence, the node running B-MAC has to listen for the preamble for (60x10) or 600ms within 1 minute. Table 7.9 compares the required idle listening periods between B-MAC and PoRAP. Note that a 32Khz timer is used in the comparison and there are 32 ticks in each millisecond.

Table 7.9: Comparison of required idle listening periods between B-MAC and PoRAP

Duration	Ticks ($x10^6$)	Required idle listening			PoRAP/B-MAC
		B-MAC		PoRAP (ticks)	
		($x10^3$) ms	ticks		
5 minutes	9.8	3	96	63	66%
10 minutes	19.6	6	192	84	44%
1 hour	118	36	1,152	449	39%
1 day	2,831	864	27,684	2560	9%

According to the comparison in Table 7.9, PoRAP requires fewer ticks in all durations. A higher conservation in the idle listening period will be obtained if there are longer durations between transmissions. PoRAP uses only 9% of the ticks for accommodating time synchronisation compared to preamble communication in B-MAC when the source sends every day. One of the main reasons is that B-MAC is specifically developed for the multi-hop wireless sensor networks where routing is necessary amongst sources. The sources have to check if there are packets addressed to them. Unlike the multi-hop, PoRAP is applied to direct communication and each source knows its communication schedule. The source is therefore often in the sleep mode.

7.4.3 Summary

This section presents analysis of the parameter space of the protocols and a comparative study. Preamble communication is the main overhead in B-MAC as the preamble length must be at least a check interval. In S-MAC, the major overhead is an active period which is provided for communication setup which includes carrier sensing, hidden node avoidance and synchronisation between neighbours. Idle listening is an important overhead in CSMA as the source always listens. Control packet reception is the main overhead in PoRAP and its size depends upon the number of sources. The limitation of PoRAP is that it is not applicable to low duty cycle applications when the percentage of slot usage is low. PoRAP conserves a significant amount of energy when it can be used. According to the comparative study, at a 300s sampling period and 50 sources, PoRAP consumes approximately 33%, 10% and 5% of the energy used by S-MAC, B-MAC and CSMA, respectively. A greater amount of conserved energy is achieved if the check and active intervals in B-MAC and S-MAC are increased. Moreover, PoRAP uses only 9% of the ticks for accommodating time synchronisation compared to the preamble communication in B-MAC when the source sends every day.

7.5 Conclusion

This chapter has provided the details of a comparative evaluation of PoRAP in terms of energy consumption. Each protocol has a different design framework and supports different communication scenarios in wireless sensor networks. After reviewing each of the protocols, the latter part of this chapter presents the analysis of the parameter space of the protocols and a comparative study. The parameter settings in the Great Duck Island [MPS+02] and B-MAC [PHC04] are adopted in the study.

The check interval and active period are overheads of B-MAC and S-MAC, respectively. In B-MAC, the preamble length is at least a check interval. An active period is used in S-MAC for carrier sensing, hidden node avoidance and synchronisation between neighbours. The default active interval of S-MAC is 115ms. Idle listening is an important overhead in CSMA as the sources listen all the time. Control packet reception is considered as an overhead in PoRAP. The size of a control packet directly relates to the number of sources.

In the comparative study, an average energy usage per second is computed. The selected sampling period and data payload are 300s and 36 bytes which are the same as [PHC04]. The chosen check interval of B-MAC is 10ms. PoRAP is not applicable to the applications which require a low duty cycle when the percentage of slot usage is low. This is because the source has to wait until all slots are completed to start a new communication cycle. A network consisting of a single source is used. In the case of 20% slot usage and 2s sampling period, PoRAP uses 16%, 43% and 48.5% of the energy of B-MAC, S-MAC and CSMA, respectively.

According to the GDI scenario and the parameter settings in [PHC04], PoRAP consumes approximately 0.2 to 0.3 x 10^{-3} mJ for transmitting one bit of data. It consumes less energy when the sampling is less often and the number of sources is higher. According to the comparative studies, PoRAP consumes approximately 33%, almost 10% and almost 5% of that required by S-MAC, B-MAC and CSMA, respectively. A larger amount of conserved energy is achieved if the check and active intervals in B-MAC and S-MAC are increased. In the case where the 200ms and 1,000ms check and active intervals are respectively chosen in the B-MAC and S-MAC, PoRAP consumes approximately 3% and 5% of the energy required by such protocols.

Further analysis of the active period required by B-MAC for preamble communications and PoRAP for accommodating time synchronisation is conducted. The 10ms check interval is used. As energy consumption directly relates to the active duration, the results demonstrate that at a 300s sampling period and a 50source topology, up to approximately 10% of the energy can be conserved if PoRAP is used instead of B-MAC. The results demonstrate that PoRAP is applicable for the low duty cycle applications. The sources benefit more from PoRAP in terms of energy conservation compared to B-MAC, S-MAC and CSMA.

Chapter 8

Future Work

This chapter describes two possible future works which are proposed to enhance the current protocol's performance. Firstly, the communication frame is split to decrease the size of the control packet. By so doing, the risk of packet corruption is reduced and the number of supported sources is increased. Additional costs such as receiving energy and clock drift are analysed. Secondly, the outline of a multiple base station system is given. All base stations agree upon the scheduling information broadcast by the master base station. Communication between base stations is therefore required in this system. In order to avoid traffic interference, multiple channel communications are employed and are supported by the current radio unit and TinyOS. Moreover, the scheduled communication between sources and base stations can be conducted simultaneously. The duration and corresponding clock drift are therefore minimised.

8.1 Introduction

The current PoRAP supports a network which consists of a base station and several sources. The sources must be located within the communication range of the base station to establish direct communication. The base station broadcasts its control packet to all its sources and the size of the control packet increases with the number of sources. The control packet carries important information including a notification of transmission power adaptation and scheduling. Approximately 117 bytes can be used for notification so a limited number of sources can be supported by the base station. A larger packet is likely to be corrupted during transmission so minimizing the packet is essential. The results in Chapter 6 demonstrate significant indoor and outdoor ranges of the sensors. However, direct communication is not applicable to a large area where the distance between sources and base station is larger than the range.

Two possible future works, a split frame and a multiple base station concept, are proposed in this chapter. A communication frame can be split to attain two main objectives. Firstly, as longer packets tend to be corrupted during data delivery, the risk of packet corruption is therefore reduced. The number of supported sources depends upon the buffering limitation of the transceiver. More sources can communicate with the base station if a control packet is split. Secondly, as communication range is considered an important factor in direct communication, the concept of multiple base stations scattered over the area of interest is introduced. Each base station collects data from its sources and forwards the processed data to the master base station. Therefore, communication between base stations is crucial and multiple channel communications are used to avoid traffic interference.

8.2 Split Frame

PoRAP currently supports a system consisting of sources and a base station. Control packet reception is considered as an overhead in PoRAP and its size increases with the number of sources. A longer control packet tends to be corrupted during the transmission. Furthermore, newly joined sources may be switched on during the frame transmission. The sources have to be in an idle mode with their radio on for a longer period waiting for the new frame to receive the control packet. A feasible solution is to split the control packet into several messages to reduce the packet size, but the overhead tends to increase. This section describes the concept of splitting a control packet.

Broadcasting a control packet to all connecting sources only once in each frame may give rise to several concerns. Firstly, the number of sources is constrained by the limited buffering capacity of radio unit which is 128 and 256 bytes for the CC2420 and CC1000 motes, respectively. The size of the remaining payload may not be sufficient to signal the power adaptation to all sources. Secondly, it is feasible for a long control packet to be corrupted during broadcast so some sources may inaccurately adapt their current transmission power. This section introduces the concept of splitting the control packet. Both advantages and disadvantages are also outlined.

8.2.1 Concept

Figure 8.1 describes the concept of splitting a control packet. Instead of having only one frame which consists of a control slot followed by data slots for all sources in the network, the frame is split into p sub-frames. Each sub-frame begins with a control slot followed by fewer data slots and supports a specific number of sources equal to that of the data slots.

According to this concept, there will be p control packets which are smaller than the current approach. A key assumption is that each source knows which control packet it should receive. For example, in a network that consists of 100 sources and a base station, the control packet in the current PoRAP scheme is 6 bytes for packet identification and scheduling details plus 25 bytes for the power adaptation notification. In the proposed enhanced scheme, only 5 bytes will be used for signaling power adaptation giving (5*4) or 20 sources if five sub-frames are used instead. In total 5 control packets are broadcast to the 100 sources. Only (6+5) or 11 bytes are required for each control packet.

However, an additional byte for frame identification is required. The control packet is broadcast to all sources within the range. Upon receiving the control packet, the source checks if the packet is addressed to it. In the case of p equal to 5, the values of the additional `frame_id` field will range from 1 to 5. The sources discard the control packet and stop their radios if the received packet is not addressed to them. Otherwise, they reset their transmission schedule and adjust their transmission power. Additional receptions are therefore required by the sources.

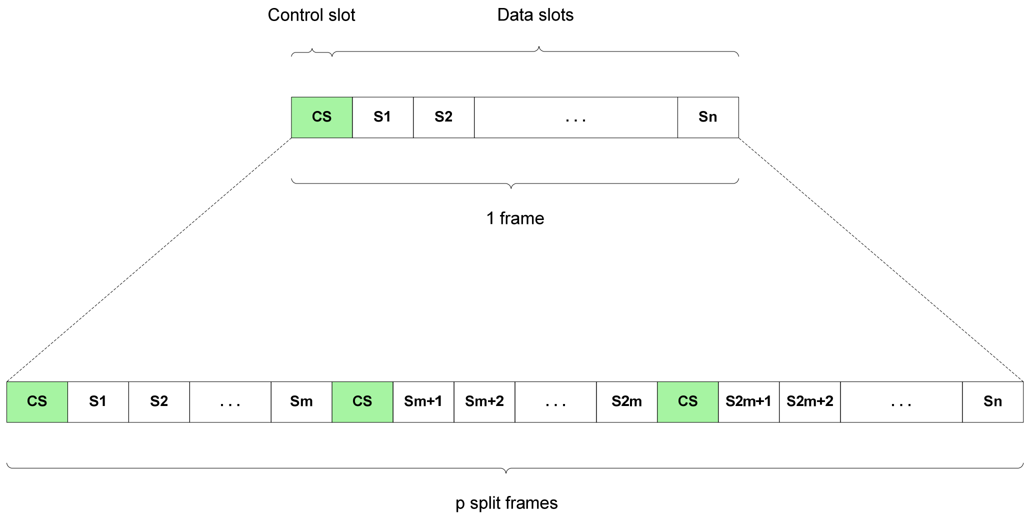


Figure 8.1: Concept of splitting control packet

8.2.2 Analysis of additional costs

The frame splitting concept is able to enhance the current PoRAP by supporting more sources. Additional costs include delay, receiving energy and clock drifts are analysed in this section.

A) Assumptions and variable settings

Four assumptions are listed as follows:

1. The number of sources equals the allocated data slots.
2. Control and data slots have the same slot length.
3. No change to the slot length is required for a split control packet.
4. The benefit of consuming less receiving energy on a smaller control packet is insignificant compared to the additional cost of receiving more control packets by the sources.

Prior to describing the analysis in more details, several variables are set as follows:

Let n be the number of data slots

p be the number of split frames which is equal to the number of control slots

l be the slot length in milli-seconds (ms)

d	be the reception delay for a slot
rx	be the receiving power in milli-watts (mW)
RD	be the control packet receiving delay in milli-seconds (ms)
c	be additional clock drift in ms
w	be the width of variations in clock drift
E_r	be additional receiving energy in milli-joules (mJ)

B) Delay

In this analysis, reception delay is defined as the duration required for control packet reception. In the current approach, a frame begins with a control slot followed by n data slots. Regarding the second assumption, the frame reception delay for the current PoRAP approach, RD_c, is shown in Equation (8.1).

$$RD_c \quad = \quad (1 + n)\, d \tag{8.1}$$

In the case of a split frame, there are p control slots whilst the number of data slots remains n. Hence, the total frame reception delay for the split concept, RD_s, can be expressed by Equation (8.2).

$$RD_s \quad = \quad (p + n)\, d \tag{8.2}$$

Subtracting Equation (8.2) from (8.1), the additional delay is $(p - 1)d$. The proposed split frame approach thus requires $(p - 1)$ more control slots or packets.

C) Receiving energy

Additional control packets and corresponding transmitting and receiving energy are required for the proposed scheme. It is assumed in this dissertation that the base station has an extra source of power. Additional transmitting energy at the base station is not therefore considered. All sources have to receive control packets to check if packets are destined for them. Additional energy is consumed and is obtained by multiplying the additional delay with the receiving power, rx. Equation (8.3) shows the additional receiving energy, E_r, in milli-joules (mJ).

$$E_r \quad = \quad (p - 1)\, d * rx \tag{8.3}$$

D) Clock drift

As the total frame size is increased by $(p-1)l$, its effects on the clock drift should be investigated. Equation (8.4) shows the associated additional clock drift (c) with respect to the width of variations in clock drift, w in ms.

$$c \quad = \quad (p-1)\, l * w \quad \leq \quad (p-1)\, l * 20 * 10^{-6} \tag{8.4}$$

where 20 ppm ($20*10^{-6}$) is the clock drift of a 32KHz watch crystal suggested by [CMR200]. Clock drift increases with the larger frame size. Guards between frames are required to accommodate the clock drift especially when there are many sources connecting to the base station. The maximum length of the guard between frames is demonstrated by Equation (8.4). Measurements shown in Figure 6.17 indicate that observed clock drifts are less than the recommended value by [CMR200] or 20 ppm.

8.2.3 Summary

The current frame structure in PoRAP includes a control slot followed by several data slots. The control slot accommodates control packet broadcast and reception. The control packet includes scheduling information and power adaptation notification. The number of notification bytes depends upon the number of sources. A byte is used to signal power adaptation to 4 sources. The control packet size is significantly increased when many sources are deployed. Control packet corruption may occur during the delivery.

An enhanced approach, the split frame, is introduced. Instead of broadcasting only one control packet, additional packets are delivered to the sources. The size of sub-frame’s control packet is therefore decreased. Two advantages are noted. Packet corruption can be decreased and there are more bytes available within a frame to increase the possible number of sources. However, several additional costs are incurred. Firstly, the split control packet length is increased as frame identification is required. The sources can check whether the received packet is destined for them. Additional duration, reception delay and clock drift are linearly related to $(p-1)$ where p is the number of split frames.

8.3 Multiple Base Stations

PoRAP is specifically developed for direct communication in WSNs. Unlike the multi-hop approach, the sources have to be located within the communication range. In order to apply direct communication to a large area, multiple base stations are required and they can be scattered over the area of interest. The base station collects the data from its sources and forwards the processed data to the master base station. Therefore, communication between base stations is crucial. This section aims to describe the concept of a multi-base station system.

Figure 8.2 illustrates the concept of multi-base station system.

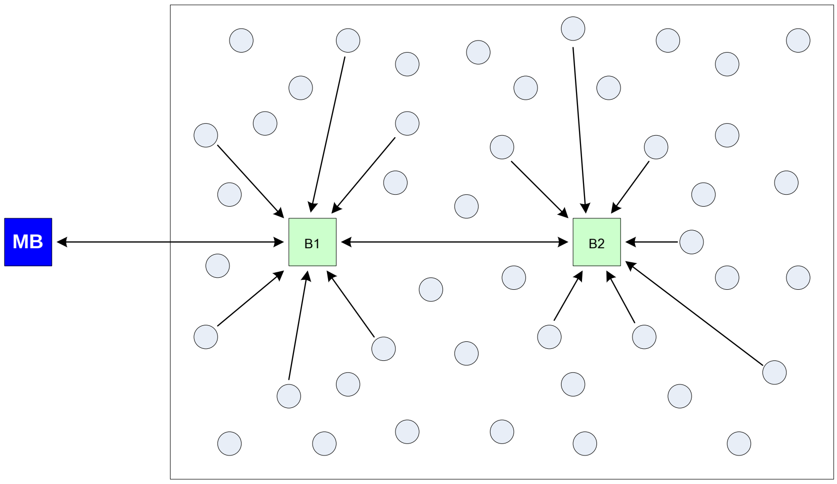


Figure 8.2: Concept of multi-base station system

According to Figure 8.2, there are two base stations (B1 and B2) and master base station (MB) which is located outside the area of interest. Some sources cannot send their data to MB directly. B1 and B2 are used to receive and forward the data to MB. Figure 8.3 illustrates the communication mechanisms in this scenario.

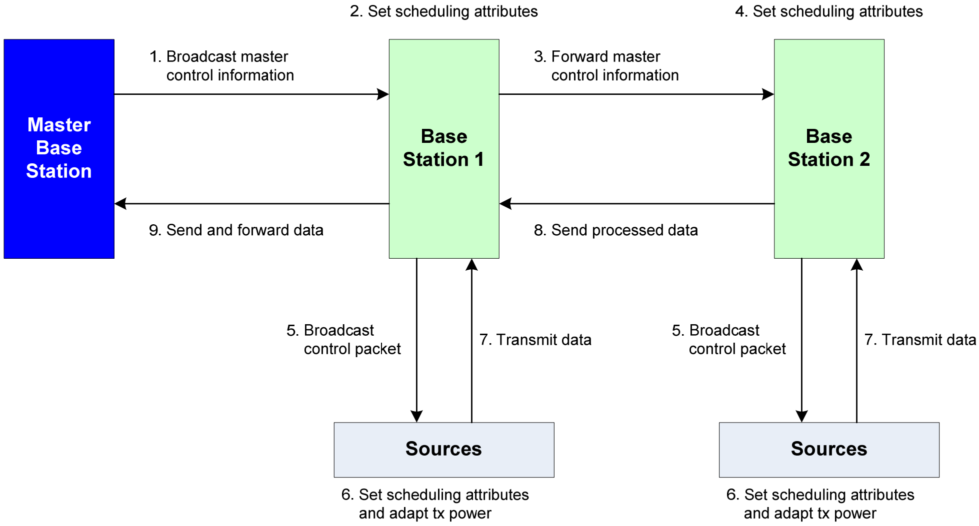


Figure 8.3: Processes in multi-base station system

Several processes are observed from Figure 8.3 and they are described as follows:

1. The master base station broadcasts its control packet to the base stations, on a changing frequency depending on the application, located within its communication range. Any

additional packet types should be defined to the master packet. There may be a case where sources receive the master packet. The sources discard the packet as it is not addressed to them.

2. Regarding the scenario shown in Figure 8.2; the base station 1, B1, is in range. It sets the scheduling attributes after receiving the master packet.

3. B1 forwards the master packet to B2 which is not located within the MB’s range.

4. B2 sets its scheduling attributes with respect to the forwarded packet. Both base stations are ready to communicate with their sources.

5. B1 and B2 broadcast the control packets to their sources. The control packets include scheduling information and notification of the transmission power adaptation.

6. The sources set their schedules and adjust their transmission power. The source-to-base station communications can take place simultaneously in the different base station’s coverage.

7. The data is sent by the sources to the base station.

8. Data is finally sent to the master base station, but a base station may conduct data processing and transmit the processed output to the neighbouring base station rather than sending raw data.

9. B1 sends its processed result along with the received one from B2 to the master base station.

The above nine processes are included in one communication cycle. They are repeated when the next cycle begins.

8.3.1 Multi-channel communications

In order to minimise the duration required for each cycle, the source-to-base station traffic can take place simultaneously. Multiple channels are therefore required. Both CC2420 and TinyOS support the multi-channel communications. The channel can be set at compilation time and ranges from 11 to 26 which is the default channel.

8.3.2 Summary

The concept of multiple base station system is introduced to enhance PoRAP's performance. In a large area, some sources may be outside the communication range and direct communication is not feasible.

Multiple base stations are scattered over the area to collect data from their sources. Hence, communication between base stations is required. As PoRAP is a schedule-based protocol, the base stations have to agree upon the communication schedules. The master control packet, which includes scheduling information, is broadcast and the base stations set their attributes accordingly.

The source-to-base station traffic can be conducted simultaneously in order to minimise the overall duration and associated clock drift. Both the CC2420 and TinyOS facilitate multi-channel communications. The channel can be set at compilation time.

8.4 Conclusion

PoRAP currently supports a system consisting of sources and a base station. Control packet reception is considered as an overhead in PoRAP and carries important signals such as notification of transmission power adaptation and scheduling information. The number of supported sources is constrained by the limited buffering capacity, which is approximately 117 bytes excluding header. Longer packets tend to be corrupted during transmission. In direct communication, the sources communicate with their base station only if they are located within the communication range.

Two possible future works have been introduced and described. Firstly, the frame may be split to reduce the size of the control packet. The risk of packet corruption is therefore also decreased. A smaller packet may be used to support a specific number of sources and, using the frame splitting concept, the number of sources supported by the base station can be increased. However, additional costs from duration, receiving energy and clock drift should be taken into account. The sources have to receive more control packets including the packets that are not addressed to them.

Secondly, a multi-base station system is outlined to enhance the performance of a direct communication scheme. Multiple base stations are scattered over the target area. The processes required for this type of system are listed and discussed. The master base station is defined as the final destination for data and it also controls the other base stations by broadcasting master control packets which include scheduling information. The source-to-base station traffic can take place simultaneously by using multi-channel communications. Hence, traffic interference can be reduced.

Chapter 9

Conclusion

This chapter presents the conclusion of the dissertation. All of the works and associated methodologies required for PoRAP development are also described. The key contributions consist of a survey of energy aware protocols for wireless sensor networks, an investigation of the relationships between link quality metrics, and the design, development and evaluation of the new protocol. PoRAP aims to provide an efficient data delivery in the single-hop manner where direct communication between sources and base station is feasible. Three major elements of PoRAP include direct communication, transmission power adaptation and a slot based scheduling algorithm. Several experiments were conducted to evaluate and quantify the amount of conserved energy, achieved packet reception rate and accuracy of scheduling. Finally, the thesis statement is stated and its significance and validity are evaluated.

9.1 Introduction

This dissertation mainly focuses on a development of a power conservation protocol for wireless sensor networks (WSNs) where direct communication between sources and base station is feasible. Whilst the multi-hop approach has been regarded as the underlying communication paradigm in WSNs, there are some scenarios where direct communication is applicable and a significant amount of communication energy can be saved. Power & Reliability Aware Protocol (PoRAP) is developed in this dissertation and its main objective is to provide efficient data communication by means of energy conservation whilst reliability is maximised.

This chapter concludes the key aspects of the dissertation. In total five key aspects are addressed;

- **Summary of work**: The undertaken works and associated methodologies are summarised.

- **Argument Précis**: The arguments are summarised and how they relate to the existing works are described.

- **Work Contribution**: A description of the contributions of the dissertation is provided. Designing a MAC protocol for a class of applications where the goal is energy conservation allows transmission to be optimised with respect to energy usage. The key contributions include a survey of protocols, an investigation of the relationships between link quality metrics and the design, development and evaluation of the new protocol.

- **Thesis statement**: The thesis statement is demonstrated.

- **Evaluation of significance and validity of the thesis statement**: A critical evaluation of the thesis statement is given and validated against statistical evidence.

9.2 Summary of Work

In this dissertation, an energy conservation protocol, Power & Reliability Aware Protocol (PoRAP), is developed to provide an efficient data delivery in wireless sensor networks (WSNs) where direct communication between sources and base station is feasible. The analysed application is a periodic-based one such as an environmental monitoring system where energy saving is a major concern. PoRAP has been developed and supports a fixed set of sources or nodes.

Prior to protocol development, a survey of energy aware protocols was conducted. The energy conservation issue is crucial in WSNs as the sensors are resource constrained. The main goal is to use the minimal amount of energy whilst the required rate of successful delivery is maintained. As WSNs are a shared medium system, the Medium Access Control (MAC) protocol is required to resolve contention. Modern transceivers provide programmable transmission power capabilities. Power adaptation is applied to transmission energy depending upon the observed link quality metrics. A specific protocol development is required due to the limited resource and application specific properties in WSNs.

Simulations were run in order to investigate the proportion of energy required for communication in WSNs and what amount of energy can be saved as a result of adaptive transmission power. Apart from power adaptation, the transceiver is capable of measuring link quality metrics such as the Received Signal Strength Indicator (RSSI), when the packet is being received. Two sets of measurement studies were conducted to motivate PoRAP design development. The first aimed to explore the relationships between location, transmission power and metrics. Packet Reception Rate (PRR) was also used as it is directly related to reliability. The main goal was to discover an optimal region where data loss is not reduced further by increasing transmission power and where reducing transmission power does not increase the loss. Hence, the sensors could operate optimally at that region to conserve transmission energy. The second focuses on establishing the relationship between packet size and communication delays. Time synchronisation is important in the schedule based system. The size of slot must be large enough to accommodate both receiving and transmitting delays. The delays can be estimated by the proposed models.

PoRAP consists of three main elements; direct communication, adaptive transmission power and scheduling. It is developed to provide an efficient data communication in single-hop WSNs where the sources communicate directly with their base station. According to [Tmote], the sensor has 50-m indoor and 125-m outdoor ranges. A significant amount of energy required by message forwarding can be saved in the single-hop scenario. PoRAP adopts the Transmission Power Control (TPC) approach to conserve transmission energy. The adaptation criterion depends upon the relationship between RSSI and PRR. A lower power can be used for transmission without further data loss. The RSSI is used as the main metric reflecting the current link quality as it is supported by the CC1000 and CC2420 transceivers. In PoRAP, a control message is broadcast by the base station and includes the notification of transmission power adaptation based upon RSSI measurements. A schedule based scheme is also adopted in PoRAP. A frame is used to represent a communication cycle. It begins with a control slot followed by several data slots and perhaps a silent period which is used to adjust the duration to conform the required duty cycle. Several components in TinyOS are modified.

The three main subjects are evaluated. Firstly, both a free space propagation model and measurements from Section 4.4.3 and associated literature [SKPP07] were used to estimate the feasible indoor and outdoor ranges at various transmission power levels. This study is important to establish the possibility of single-hop WSN deployment. The RSSI of -95 and -85 dBm were used to determine the ranges. The -95 dBm is the lowest value which is reported by the transceiver whilst the -85 dBm does not provide further packet loss according to the measurements in Chapter 4. Experiments were conducted to investigate the benefits of direct communication compared to multi-hop communication. A line topology was used in each study. The required transmission power was obtained from the previous measurements. A higher power is required by direct communication and it is compared to the additional power required for message forwarding in the multi-hop senario. Further, the effects of distances and source densities were studied. This helps to establish which specific network topology benefits the most from direct communication.

Secondly, energy savings achievable with transmission power adaptation were analysed. A network consisting of 10 sources was deployed in an indoor environment. The sources were located at ten different distances; 1, 2, 4, 6, 8, 10, 12, 14, 16 and 20m. In total four different RSSI settings were used and the maximum power was used as a reference. The goal was to quantify the amount of saved transmission power and data loss. Finally, the accuracy achieved with scheduling was investigated. Clock drift is important in a schedule based system like PoRAP. It is caused by different speeds of different local clocks. Clock drifts were measured in a 20-source network topology. The observed magnitudes were compared to the 20 parts per million (ppm) recommended by [CMR200]. Further, the durations between two consecutive transmissions were varied to determine the effects. The results were analysed to explore how the prediction of clock drifts relates to further minimisation of idle listening.

In the comparative study, PoRAP's performances in terms of power conservation were compared to those of CSMA, S-MAC and B-MAC. Each protocol has a different design framework and supports different communication scenarios in WSNs. The effects of the parameter space of each protocol on energy consumption were established. The scenario in Great Duck Island (GDI) [MPS+02] was used and the methodology used in [PHC04] was adopted in this study. An average energy usage per second is chosen as a metric. Further analysis of the active period required by B-MAC for preamble communications and PoRAP for accommodating time synchronisation is conducted. The study aims to compare required listening periods between contention and schedule based approaches under various durations between two consecutive transmissions.

PoRAP is similar to [EQ07] as scheduling information is included in the control packet. However, clock drift is noted as an important factor but not determined in [EQ07] whilst it was measured in PoRAP. Furthermore, additional message exchanges amongst sensors are not required in PoRAP as the base station periodically broadcasts and is the reference node in the system. Time synchronisation refers to the timestamps performed at the MAC layer in order to eliminate several non-deterministic delays which mainly depend upon processing speed and operating system interrupt [MKSL04].

In summary, a significant amount of work has been conducted in this dissertation. A survey of existing related works, simulation, measurement, design, development, testing and evaluation have been made to prove that PoRAP can be used in WSNs where direct communication is feasible and energy conservation is achievable. Power and resource constraints, application specific, shared medium systems and variability in link quality are taken into consideration during the design and development processes. The scenario from a major production WSNs application, the Great Duck Island (GDI), along with the methodology used in the associated protocol [PHC04] were used in the evaluation and comparative study.

9.3 Argument Précis

PoRAP is a measurement and schedule based protocol for the single-hop WSN. It has been developed for the periodic-based application where energy conservation is major concern instead of bandwidth utilisation. PoRAP adopts the transmission power control scheme to conserve transmission energy. Lower power can be used for data transmission without unnecessary data losses. This section aims to provide several key arguments of PoRAP design and development.

9.3.1 Special requirements for protocol development for WSNs

To develop a communication protocol for WSNs requires a substantial work. There are two main reasons. Firstly, a sensor is power and resource constrained. The sensor can be considered as a small computer which is able to communicate, process and storage data. Wireless sensor networks

(WSNs) consist of sensors and base stations connected wirelessly. All of the power is from tiny batteries. WSNs can be deployed in both friendly and hostile environments. The recharge and replacement of batteries are unlikely especially in remote or hostile environments. Energy conservation should therefore be considered during the protocol design. The hardware components of a sensor are miniaturised to fit into a small circuit board. The size of memory and buffering capacity are smaller than a traditional desktop or laptop computer. Message exchanges between nodes are the norm in the communication protocol. Larger packets may not be received and stored in the transceiver's buffer [CC2420].

Secondly, WSNs are considered application specific. They were invented for the military or surveillance applications. At present, they have been deployed in a wide range of civil applications. Each application has its own set of requirements. There are two main categories of the WSNs application; event-based and periodic-based. An event-based application requires a high data reporting rate when an event of interest occurs. An example of the event-based is an intruder detection system [ADB+04, SBP+04]. In the case of a periodic-based application, power conservation is the major concern instead of throughput. Habitat and environmental monitoring systems are categorised as periodic-based applications [MPS+02, MPR+05].

According to both characteristics, developing a general purpose protocol for WSNs is thus unlikely. The review of the existing applications in Section 2.1 demonstrates particular development. A significant literature review of current protocols and applications has been made prior to design and development to enable PoRAP to be applicable to periodic-based applications.

9.3.2 Single-hop application in WSNs

The estimation of feasible indoor and outdoor communication ranges demonstrates applicability of the single-hop in WSNs. Data communication in WSNs is not always the multi-hop especially when the nodes are located within the communication ranges of each other. Multi-hop is always used in WSNs. Data is forwarded to the next hop which is located near to the sender to conserve power. Moreover, the multi-hop is required to cover a large area.

One of the key contributions of this work is to explore the feasibility of direct communication. The Tmote platform is used and it has 50m and 125m indoor and outdoor ranges, respectively. These values are significant. However, it is important to further analyse possible ranges based upon established models and measurements.

Data transmission in WSNs requires a line-of-sight. A free space model assumes a perfect environment without barriers and extreme weather. This model together with measurements in Chapter 4 and [SKPP07] are used. The results demonstrate that the sensor has significant ranges. The selected power levels are those specified in [Tmote]. Further analysis is made to obtain the feasible ranges of all possible 31 transmission power levels. The CC2420 transceiver is used in this study as it is employed by the Tmote platform [Tmote].

Apart from exploring the feasible ranges, three studies were conducted where the energy requirements for single and multi-hop communication were compared. A line topology was used in each study. The main reason of using a line topology is to demonstrate message forwarding in the multi-hop. The minimum power is used for the multi-hop communication. The node located nearest to the base station spends the highest amount of energy as it has to receive and transmit all messages delivered by the other nodes. This observation confirms the observation made by [Hae03, SBW09]. The sensor will benefit more from energy conservation if the node density is high as the number of data forwarding packets increases.

Direct communication can be used in wireless sensor networks. The limitation is the communication ranges of sensors. A higher transmission energy is required for direct communication but the nodes are not responsible for routing the data to its destination. In the case of CC2420 transceiver, the receiving current is 19.7 mA which is higher than the maximum transmitting current. Multiple transmissions and receptions and their associated energy are significant and they are sometimes neglected [SBW09].

9.3.3 Intelligent power adaptation and scheduling

In direct communication, the base station controls the sources which are located within its range by periodically broadcasting the control packet. Message exchanges between sources are not required. Key information in the control packet includes notification of transmission power adaptation and scheduling. Hence, the base station can be considered as a reference node in the network.

In PoRAP, the base station is also a Tmote sensor like the sources. It is assumed that the base station has an extra power from its connecting machine such as a desktop or laptop computer. The collected data can thus be delivered to the machine and may be sent via the Internet. An indoor experiment was conducted to obtain the relationships between RSSI and PRR. The results are similar to the ones in [LZZ+06] and [SDTL06]. These relationships are not affected by the environment. For example, an RSSI of over -85 dBm often produces no further data losses. However, the transmission power which provides a specific RSSI is affected by the environment. PoRAP is a measurement-based protocol which adjusts power based upon the currently observed link quality metric.

Apart from transmission power adaptation, PoRAP adopts the schedule-based scheme where a communication is represented by a frame. A time slot is allocated to each source. A frame begins with a control slot and data slots and corresponds to a duty cycle. A set of experiments was set up to study communication delays and to estimate the amount of delay. The size of slot has to be large enough to accommodate the receiving and transmitting delays. Moreover, clock drift was studied as it is important in the schedule-based system. Time synchronisation will not be maintained if the clock drift is not compensated for. The recommended duration for clock drift in [CMR200] can be used but the sources should locally adjust their schedule with respect to the variation in the drift. An experiment was conducted to investigate the clock drift prior to deployment. The sources can thus be in the sleep mode longer to minimise the energy usage.

9.3.4 Quantification of energy savings

All of the energy savings from the direct communication, transmission power adaptation and scheduling are described. In the case where five sources are uniformly distributed over a 50m line topology as shown in Figure 6.8, almost two-thirds of the transmitting current can be conserved if single-hop communication is used. Instead of always transmitting at the maximum power, further savings in the transmitting current can be made. According to Figure 6.3 where feasible indoors ranges at various power levels are given, the levels of 3, 7, 9, 13 and 16 can be respectively used at 10, 20, 30, 40 and 50m. The Tmote datasheet only provides the required current at 3, 7, 11, 15, 19, 23, 27 and 31 power levels only. Regression analysis is applied and the required transmitting current (t_c) can be computed by using Equation (9.1).

$$t_c \quad = \quad (0.3255 * t_l) + 7.6378 \qquad (9.1)$$

where t_l demonstrates the transmission power level. The R-square is over 0.99 which means that over 99% of data can be represented by the equation. The sources located at 10, 20, 30, 40 and 50m away from the base station require a current of 8.6, 9.9, 10.6, 11.9 and 12.8mA. The maximum power level consumes 17.4mA. Hence, in total (8.8 + 7.5 + 6.8 + 5.5 + 4.6) or 33.2mA can be saved. This means that {33.2mA / (17.4mA * 5 nodes) * 100} or 38% of transmitting current can be conserved as a result of transmission power adaptation compared to always transmitting at the maximum power level.

Assuming those five sources send their data to the base station every five minutes and data packet size is 36 bytes as in [MPS+02], a communication frame begins with a control slot followed by five data slots is used. The size of the control packet is 8 bytes according to Figure 5.16. According to Section 5.5.5, the size of the control and the data slots which cover all the relevant operations in the application and lower layers are respectively 12.75 and 18.50ms. Without scheduling, each source has to listen for {[(300s * 1,000) – (12.75ms + 18.50ms)] + 6.13ms} or 299,974.88ms where 6.13ms is reserved for the clock drift based upon [CMR200]. However, each source can be in sleep mode within this computed interval. According to [Tmote], sleeping consumes only 5.5% energy compared to that for listening. Hence, up to 94.5% of listening power can be saved. Moreover, a further saving of 68% of the 6.13ms is conserved if the variation in the clock drift is considered.

In summary, adaptive transmission power and scheduling respectively achieves a saving of 38% of transmitting current and 94.5% of listening current. A further 68% saving for reserved duration for clock drift is obtained.

9.4 Contributions of the Work

This section aims to demonstrate the contributions of this thesis. The development of PoRAP consists of several processes which are separately described as follows:

9.4.1 Survey of power aware protocols for WSNs

Energy conservation is crucial in protocol development as the sensor has limited power from the batteries alone. There are two main categories of the power aware protocol. Firstly, the Medium Access Control (MAC) protocol is responsible for resolving contention. WSNs are considered as a shared medium system. A MAC protocol is required to avoid two major sources of energy wastage; collision and idle listening. There are two major schemes for avoidance; the contention and schedule based approaches. Both of them have been adopted and enhanced for application specific WSNs. Sensors should be in sleep mode when they have no data to send in order to minimise idle listening. In the case of contention-based system, additional control frames are utilised to achieve the application's energy requirements. A time slot is allocated for each sensor in the schedule-based approach. Collision and idle listening can be thus avoided and minimised.

The second category takes advantage of programmable transmission power which is provided by the transceiver. The transmission power control (TPC) based schemes demonstrate two similar procedures. Firstly, a transmitting node discovers which or how many active neighbours it has by broadcasting messages. Secondly, a feedback or acknowledgement system is used after the neighbours successfully receive the messages. Several thresholds are defined to classify the link quality and each node has additional costs on storing and maintaining the neighbours table. Knowing the environmental factors may help to select an appropriate power level accurately and quickly. Once the minimum power for each sensor pair has been found, it will be used for future transmissions and the path which consumes the least power will be calculated and then used for an end-to-end data delivery. A link quality measurement should not be conducted only once as it may change over time.

9.4.2 Investigation of the relationships between RSSI and PRR

One of the key hardware components of a sensor is the transceiver as it enables data communication to the sensor. In WSNs, sensors are wirelessly connected. The radio signal is propagated to the receiver via the air. The reception strength is susceptible to environmental conditions and changes over time. The data may not be successfully delivered to its destination when the reception strength is too low. In such a case, the required reliability is not met. The Received Signal Strength Indicator (RSSI) is defined as a measurement of the signal strength of an incoming message. The RSSI is measured at the receiver and demonstrates the received signal strength. Therefore, signal attenuation is approximately the difference between the transmission power and the RSSI. Packet Reception Rate (PRR) is a reliability-related metric. It is defined as a percentage of the number of correctly received packets to that of transmitted packets.

PoRAP adopts the TPC scheme to conserve transmission energy without unnecessary data losses. Required transmission power should not be estimated from the existing models as the link quality metrics are affected by a wide range of factors. As CC2420 reports RSSI and Link Quality Indication (LQI), the relationships between the three metrics are established. The results demonstrate that a RSSI over -85 dBm does not often produce a further reduction in the PRR. Similar observations are stated in [LZZ+06, SDTL06]. The relationship between link quality metrics can therefore be used to estimate an observed reliability from the measured receiving strength. After reviewing the metrics, the base station determines whether the current transmission power requires an adaptation.

9.4.3 Protocol design

The Power & Reliability Aware Protocol (PoRAP) is developed in this dissertation and its main objective is to provide an efficient data communication by means of energy conservation whilst reliability is maintained. The Tmote platform is chosen in this study and it has a 50m indoor and a 125m outdoor ranges [Tmote]. Direct communication is therefore feasible if the sources are located within range. Associated energy required for routing is unnecessary in direct communication.

PoRAP adopts a transmission power control scheme which aims to minimise transmission energy. The chosen link quality index, RSSI, is measured by the base station while the packet is received. Another index, the PRR, is also used as it is more closely related to the reliability requirement. Experimental results demonstrate the relationship between RSSI and PRR. There is an operating region where data loss is not reduced further by increasing transmission power and where reduction in transmission power does not increase the loss. The base station compares the observed RSSI with the required RSSI range. Transmission power is decreased when the measured RSSI is less than required. However, the power is increased if the RSSI is higher. Minimum and maximum RSSI thresholds are defined with respect to the reliability requirement. Transmission power adaptation is notified by the base station via control packet broadcast. Only two bits are used for signaling the notification to each source as the buffering capacity of the radio unit is limited.

PoRAP adopts the schedule based scheme. A frame represents a communication cycle and consists of several time slots. The frame begins with a control slot and is followed by data slots. Apart from the notification of transmission power adaptation, the control packet includes scheduling information. The scheduling information consists of number of slots, slot length and the time when the first data slot starts. The control packet is broadcast at the start of every frame in order to reduce the effects of clock drift. Once the source has received the control packet, the transmission schedule is calculated from the control information. The radio is stopped and the source is switched to sleep mode. It wakes up when its slot arrives followed by another sleep mode after transmission. Further, clock drift is also determined. It is important in the schedule based system as time synchronisation may be no longer maintained if additional duration is not reserved for the drift.

9.4.4 Experimental / measurement work

Several sets of experiments were conducted in this dissertation around five subject areas. These are described as follows:

A) Estimation of feasible communication ranges

Statistical analysis was conducted to estimate the possible indoor and outdoor ranges of sensors. Both free space propagation model and the measurements in Chapter 4 and [SKPP07] were used. Two values of RSSI values, -95 and -85 dBm, were used to determine the ranges. The transceiver does not report the RSSI below -95 dBm. The -85 dBm signal often produces a steady PRR without further data losses.

The feasible ranges based upon the -95 dBm signal are 65m and longer than 1,000m for the minimum and maximum transmission power settings, respectively. Lower ranges are obtained from -85 dBm; 20m and 420m. The measurements in Chapter 4 provide the feasible maximum indoor ranges up to 96m and 38m for -95 dBm and -85 dBm, respectively. The possible maximum outdoor ranges based upon the results in [SKPP07] are up to 420m and 143m for -95 dBm and -85 dBm, respectively. Direct communication is often possible in appropriate scenarios.

B) Energy savings attributable to direct communication

Three experiments were made to study the benefits of direct over multi-hop communication. A line topology was used in each study. In the first analysis the network was divided into regions each of which corresponds to a different transmission power setting. One node was placed in each region. The minimum power level is used in the multi-hop transmission. The sources located closer to the base station benefit the most from direct communication as they consume less transmission power. These nodes require more sending and receiving power to accommodate multi-hop communication.

The distances between sources and their densities were varied in the second and third experiments. The current consumption per source increases with increasing distance between the sources for both single and multi-hop. Direct communication requires nearly one-third of the multi-hop energy. According to the effects of densities, significant increases in the consumption are observed in the multi-hop when more sources are used for message forwarding. However, the current consumption in the single-hop slightly decreases. The sources significantly benefit in the single-hop case when the source density is high. In the case where 5 sources are uniformly distributed over a 50m line topology, almost two-thirds of the transmitting current can be conserved if single-hop is used. More current will be saved in a higher density network as the number of message forwarding increases.

C) Energy savings achievable with power adaptation

One of the key requirements in the development of a network protocol is to minimise the data loss. It can be yielded by always transmitting at the maximum power. No power is saved but the packet losses are low. However, it is feasible to use a lower power without unnecessary data losses. Several RSSI settings were tested to investigate the observed PRR and conserved power.

Higher power conservation is achieved if a lower RSSI is set. The appropriate RSSI settings mainly depend upon the reliability requirement. Assuming that a network topology consisting of 10 sources located at 10 different distances, 1, 2, 4, 6, 8, 10, 12, 14, 16 and 20m; the application requires at least 99% of reliability at the base station. The appropriate RSSI setting is between -80 and -70 dBm. With this setting, almost all nodes can save energy. A total power saving of 262.1% or 26.2% per source is achieved. This implies that, with such a RSSI setting, the sources use an average 73.8% of the maximum power.

D) Accuracy achieved with scheduling

Clock drift occurs as a result of uncertainty in the sensor ticking rate. Different local clocks may run at different speeds. Clock drift may be accumulated and time synchronisation is no longer maintained. Clock drift is crucial in a schedule-based system like PoRAP. In an experiment, the base station measured the clock drifts and a statistical analysis was conducted. The results were compared to the 20 parts per million (ppm) which is recommended in [CMR200]. Further, the durations between two consecutive transmissions were varied to determine the effects. The results were analysed to explore how the prediction of clock drifts relate to further minimisation of idle listening.

The results show that clock drift is hardware-dependent and the maximum measurement is less than 20ppm for these motes. Drift also depends upon the duration between two consecutive transmissions. The measurements demonstrate that clock drift can be accounted for in the scheduling algorithm, as it happens in a predictable way, by looking at the median and variation. Hence, by measuring variation in clock drift the accuracy with which scheduling can occur is established. The base station monitors the relative clock drift to each of the sources. The measurements are broadcast to the sources and they can adjust their scheduling locally to minimize the listening period. According to the measurements, up to 95% of the reserved duration and the corresponding idle listening energy can be conserved.

E) Comparison of power requirements

PoRAP's performances in terms of power conservation were compared to those of CSMA, S-MAC and B-MAC. In GDI, the sources sent their data every 5 minutes, the sampling period was 300s. A data payload size of 36 bytes was used [PHC04]. PoRAP can be used in a patch which consists of sensing nodes and a base station. The selected numbers of sources are 1, 10, 50 and 100. An average energy usage per second was used as in [PHC04].

In the case where a source sends every 0.1s, PoRAP uses 16%, 44% and 67% of the energy of B-MAC, S-MAC and CSMA, respectively. Less energy is consumed by PoRAP at longer periods up to 300s which was used by [MPS+02] and [PHC04]. At a 1,000s sampling interval, PoRAP consumes 12%, 34% and 5.5% of the energy used by B-MAC, S-MAC and CSMA. A significant amount of energy can be saved by PoRAP when it is applicable.

PoRAP is not significantly affected by the number of sources compared to S-MAC and B-MAC as intermediate nodes are not required for data forwarding. The main limitation of PoRAP is that it is not applicable to the high duty cycle applications when the percentage of slot usage is low. However, it can conserve a higher amount of energy than the other protocols when it can be used. The main reason is that it does not require multiple transmissions and receptions. Further, the sources are periodically switched to sleep mode to conserve energy.

9.5 Thesis Statement

The thesis statement is as follows:

"Significant gains in power conservation can be achieved by designing WSN protocols to meet specific application classes. Specifically, that combining direct communication, power adaptation and intelligent scheduling is appropriate for sensor networks spread over moderate distances with regular reporting patterns where maximising bandwidth is not the prime requirement."

9.6 Evaluation of Significance and Validity of Thesis Statement

PoRAP has been designed and developed for the periodic-based class of WSN application where power conservation is the prime concern rather than maximising bandwidth. An example of the targeted application is a habitat or environmental monitoring system. A production application whose parameter settings were used in the evaluation is the Great Duck Island (GDI) project [MPS+02]. The sensors reported their data to the base station every 5 minutes and the network was expected to run for 9 months. In order to achieve these requirements, communication energy has to be minimised.

PoRAP is a specifically developed network protocol for the single-hop WSNs. Experimental results demonstrate significant benefits of direct communication as it does not require data forwarding between the hops. Estimated indoor and outdoor ranges are significant and the single-hop is thus applicable in several classes of WSN applications. Transmission power, distance, reception strength and reliability are related. The RSSI-PRR relationships were investigated in this dissertation and related works [LZZ+06, SDTL06]. The relationships are similar in various environments. There is an optimal region where steady reliability is obtained without further reduction in the PRR. These relationships can be used to appropriately set the minimum and maximum RSSI to achieve a required reliability. A lower power can often be used and the corresponding power is decreased.

The base station is considered as a reference point in the single-hop network for the sources to synchronise with. The sources can be in sleep mode most of the time and they wake up only for control reception and data transmission. The measurements of clock drift make it possible to further reduce the listening period required for the synchronisation. By considering the median and variations in the drift, the reserved period for clock drift can be reduced.

All of the results demonstrate the validity of the thesis statement. The feasible ranges of the sensors are significant. Adaptive transmission power yields a reduction in transmission energy without unnecessary data losses. Intelligent scheduling demonstrates accuracy in the communication whilst the clock drift is efficiently accommodated. PoRAP is the first power conservation protocol specifically developed for direct communication WSNs.

Two possible enhancements of PoRAP are discussed in terms of limited range and dynamic topology change. Firstly, it supports the network which consists of sources and a base station. PoRAP is not currently applicable to a large area where the dimensions are larger than the communication ranges. In this case a multiple base station system is required and this concept was discussed in Chapter 8. Secondly, PoRAP is not appropriate in a network where the topology frequently changes. Some nodes may join or leave the network at any time. A specific number of slots are set in PoRAP prior to operation. In the case of PoRAP, the nodes are left to operate by themselves at their locations with minimal human intervention throughout the predefined network lifetime.

9.7 Conclusion

This chapter concludes the key details of the dissertation. The Power & Reliability Aware Protocol (PoRAP) is developed in this dissertation and its main objective is to provide an efficient data communication by means of energy conservation whilst reliability is maintained. Its three key elements include direct communication, adaptive transmission power and intelligent scheduling. The estimated indoor and outdoor ranges demonstrate feasibility of direct communication at moderate distances. With adaptive transmission power and intelligent scheduling, the power consumption is minimised as a result of a lower transmitting power, collision avoidance and minimised idle listening without unnecessary data losses.

The key capabilities of PoRAP make it suitable for use in the periodic-based WSN applications with regular reporting patterns where maximising bandwidth is not the prime concern. PoRAP thus applies to some of the WSN applications such as environmental and habitat monitoring where the sources often remain at their positions throughout the operation. Slots are allocated to the sources for data transmissions. In PoRAP, it is assumed that the number of allocated slots is equal to that of sources. A low duty cycle application is more efficient using PoRAP when the percentage of slot usage is high. However, PoRAP is not applicable if a source has to wait longer until the next cycle is started. Therefore, a limitation of PoRAP arises when there is a high slot overhead because there are many sources in the network.

A significant amount of work has been conducted in this dissertation. A survey of existing related works, simulation, measurement, design, development, testing and evaluation have been made to prove that PoRAP can be used in the single-hop WSNs where energy conservation is the major concern instead of bandwidth utilisation. All of the key characteristics of WSNs; power and resource constraints, application specificity, shared medium systems and the variability in link quality are taken into consideration during the design and development processes. Several parameter settings and methodologies in the GDI [MPS+02] and [PHC04] were adopted in the comparative studies in terms of energy conservation.

Appendix A

Calculation of Average Energy Usage per Second

This appendix aims to provide the calculation details for the average usage per second which is used as a metric in Chapter 7. The procedures are the same as in [PHC04].

A.1 Parameters

This section provides the definitions of parameters which are used by all protocols.

Let	s	be the sampling period in seconds (s)
	r	be the data reporting rate in packets per second equal to $1/s$
	p	be the data payload sizes (bytes)
	d	be the data rate in kilobits per second (kbps) which is 250 kbps specified by the Tmote Sky datasheet
	d_o	be the observed data rate in kilobits per second (kbps) which is 65% of d and is equal to 162.5 kbps
	t_b	be the duration required for transmitting or receiving 1 byte of data.
	n	be the number of neighbours or number of sources in PoRAP
	tx	be the transmitting power in milli-watts (mW)
	rx	be the receiving power in milli-watts (mW)
	lx	be the listening power in milli-watts (mW)
	sx	be the sleeping power in milli-watts (mW)
	t_d	be the transmission delay in seconds (s)
	r_d	be the reception delay in seconds (s)
	l_d	be the listening delay in seconds (s)
	s_d	be the listening delay in seconds (s)
	E_t	be the transmission energy in micro-joules (μJ)
	E_r	be the reception energy in micro-joules (μJ)
	E_l	be the listening energy in micro-joules (μJ)
	E_s	be the sleeping energy in micro-joules (μJ)

A.2 Calculation of Communication Delays

Prior to computing the energy, communication delays have to be calculated. Section 7.3.2 describes the theory of the calculations. This section separately provides the details of each protocol.

A.2.1 B-MAC

The key procedure in B-MAC is the preamble communication which is also determined as a major overhead. The preamble length is at least a check interval. Let t_{txb} and t_{rxb} represent the durations required for transmitting or receiving 1 byte in micro-seconds (μs). Theoretically, both values are equal and are represented by t_b as shown in Equation (A.1).

$$t_b \quad = \quad t_{txb} \quad = \quad t_{rxb} \tag{A.1}$$

Equation (A.2) is used for calculating t_b.

$$t_b \quad = \quad (8 / d_o) * 10^3 \tag{A.2}$$

Let c_{int} represent the check interval in milli-seconds (ms). The length of preamble in bytes, $l_{preamble}$, is computed by using Equation (A.3).

$$l_{preamble} \quad = \quad (c_{int} / t_b) * 10^3 \tag{A.3}$$

The communication delays in milli-seconds (ms) are calculated as follows:

- Transmission delay (t_d) – is equal to the product of the data reporting rate (r), length of preamble plus data payload ($l_{preamble} + p$) and the duration required for transmitting 1 byte of data (t_b) as shown in Equation (A.4).

$$t_d \quad = \quad r * (l_{preamble} + p) * t_b * 10^{-3} \tag{A.4}$$

- Reception delay (r_d) – is equal to the product of the attributes used in the transmission delay and the number of neighbours (n) as shown in Equation (A.5).

$$r_d \quad = \quad r * (l_{preamble} + p) * t_b * n * 10^{-3} \tag{A.5}$$

- Listening delay (l_d) – is equal to the product of the total duration for wakeup (w), 4.18ms [Lim06] and the channel sampling frequency. The inverse of check interval (c_{int}) is the channel sampling frequency. Equation (A.6) shows the calculation of the listening delay.

$$l_d \quad = \quad w / (c_{int} * 10^{-3}) \tag{A.6}$$

- Sleeping delay (l_d) – is the remaining time in 1 second after subtracting the other delays as shown in Equation (A.7).

$$s_d \quad = \quad 1 - (t_d + r_d + l_d) \tag{A.7}$$

A.2.2 S-MAC

Additional control frames are required for synchronisation and hidden node problem avoidance. The frames include SYNC, RTS, CTS and ACK. Let l represent the length and its subscript be the frame type. For example, l_{SYNC} is the length of SYNC in bytes.

The communication delays milli-seconds (ms) are calculated as follows:

- Transmission delay (t_d) – a source transmits SYNC, RTS and DATA to its neighbours. Upon reception, it sends CTS and ACK frames. The number of CTS and ACK transmissions is equal to the number of neighbours. The transmission delay is equal to the product of data reporting rate (r), the total length of transmitted frames and the duration required for transmitting 1 byte of data (t_b) as shown in Equation (A.8).

$$t_d \quad = \quad \{[(l_{SYNC} + l_{RTS} + p)] + [(l_{CTS} + l_{ACK}) * n]\} * t_b * r * 10^{-3} \tag{A.8}$$

- Reception delay (r_d) – each source receives SYNC, RTS, CTS, DATA and ACK frames from all of its neighbours. Reception delay is equal to the product of the attributes used in the transmission delay plus the number of neighbours as shown in Equation (A.9).

$$r_d \quad = \quad [(l_{SYNC} + l_{RTS} + p + l_{CTS} + l_{ACK})] * n * t_b * r * 10^{-3} \tag{A.9}$$

- Listening delay (l_d) – is equal to the remaining duration within an active duration (act) as shown in Equation (A.10).

$$l_d \quad = \quad act - (t_d + r_d) \tag{A.10}$$

- Sleeping delay (s_d) – is the remaining time in 1 second after subtracting the other delays as shown in Equation (A.11).

$$s_d \quad = \quad 1 - (t_d + r_d + l_d) \tag{A.11}$$

A.2.3 CSMA

The sources always listen and they are not switched to sleep mode in CSMA. The listening energy therefore accounts for a significant amount of the total communication energy.

The communication delays milli-seconds (ms) are calculated as follows:

- Transmission delay (t_d) – a source transmits its data to its neighbours located within the communication range. Transmission delay is equal to the product of data reporting rate (r), data packet size (p) the duration required for transmitting 1 byte of data (t_b) as shown in Equation (A.12).

$$t_d = r * p * t_b * 10^{-3} \tag{A.12}$$

- Reception delay (r_d) – each source receives data from all of its neighbours. Reception delay is equal to the product of the attributes used in the transmission delay plus the number of neighbours as shown in Equation (A.13).

$$r_d = r * p * t_b * n * 10^{-3} \tag{A.13}$$

- Listening delay (l_d) – is equal to the remaining active duration after subtracting transmission and reception delays from 1 second as shown in Equation (A.14).

$$l_d = 1 - (t_d + r_d) \tag{A.14}$$

- Sleeping delay (s_d) – the sources are not switched to sleep mode in CSMA as they listen all the time. Thus, the sleeping delay is zero as shown in Equation (A.15).

$$s_d = 0 \tag{A.15}$$

A.2.4 PoRAP

Several delay estimation models proposed in Section 5.5.4 are obtained from experimental results used for calculating the communication delays. The size of the control packet depends upon the number of connecting sources. Two bits are required for signaling power adaptation to each source. The average energy usage per second is the metric so the goal is to discover the communication delay in 1 second.

The communication delays milli-seconds (ms) are calculated as follows:

- Transmission delay (t_d) – a source transmits its data directly to its base station. Transmission delay is equal to the product of the data reporting rate (r) and the transmission delay for sending a data packet (td_{data}) as shown in Equation (A.16)

$$t_d = r * td_{data} \tag{A.16}$$

- Reception delay (r_d) – each source receives the control packet broadcast from the base station. Reception delay is equal to the product of the data reporting rate (r) and the reception delay for receiving a control packet ($rd_{control}$) as shown in Equation (A.17)

$$r_d = r * rd_{control} \tag{A.17}$$

- Listening delay (l_d) – there are three listening components at the source. Firstly, the source listens whilst the control packet is prepared and delivered to the lower layers at the base station l_{d1}). Secondly, an additional listening period is required for the control packet reception until the complete receiving event is signaled at the source's application layer (l_{d2}). Finally, the source listens when its data packet is being prepared at the application layer and delivered to the lower layers (l_{d3}). The listening delay is equal to the product of the data reporting rate (r) and the summation of the three listening components as shown in Equation (A.18)

$$l_d = r * (l_{d1} + l_{d2} + l_{d3}) \tag{A.18}$$

- Sleeping delay (s_d) – is the remainder in 1 second after subtracting the other delays as shown in Equation (A.19).

$$s_d = 1 - (t_d + r_d + l_d) \tag{A.19}$$

A.3 Calculation of Total and Average Energy Consumption

The energy consumption in micro-joules (μJ) is obtained by multiplying the power with the corresponding delay. For example, the transmission energy (E_t) is equal to (t_d * tx). The total energy consumption is the summation of transmission, reception, listening and sleeping delays. The average energy usage per second is equal to the ratio of the total energy consumption to the number of data bits.

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